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13. SUPPLEMENTARY NOTES This is a presentation to be given as an invited talk at NASA Ames Research Center.					
14. ABSTRACT Combustion instabilities have been observed in nearly every major liquid rocket engine development effort, including the most recent development programs. They are caused by the coupling of the natural acoustic modes of the combustion chamber with the dynamics of the heat release, which can in turn lead to catastrophic damage of the internal components of the rocket engine. Rayleigh's criterion states that combustion instabilities are driven when the pressure waves and the heat release are in phase and that the instabilities are damped when they are out of phase. Despite the simplicity of this relationship, the prediction of the occurrence of combustion instabilities has proven to be an enduring challenge because of the inherent complexities in the physics of multiphase turbulent flames. The Air Force Research Lab (AFRL)'s Advanced Liquid Rocket Engine Stability Technology (ALREST) program is a coordinated effort that involves both modeling and experimental components at various universities, small business, industry and in-house. The overall approach is to conduct data-centric, multi-fidelity combustion stability model development. "Data-centric" means that all model development is directed at experimental data sets. "Multi-fidelity model development" means that the most effective way to advance modeling capability is to do it simultaneously at multiple levels of fidelity. The talk will focus particularly on the modeling efforts of two experimental datasets obtained at Purdue University, which involve self-excited high-amplitude acoustic instabilities in longitudinal-mode and transverse-mode rocket chambers. In both cases, Detached Eddy Simulations of the turbulent reacting flowfield are shown to be effective in predicting the instability phenomena and the associated trends. In addition, the talk will also provide a general overview of rocket propulsion activities at AFRL.					
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Progress and Challenges in Liquid Rocket Combustion Stability Modeling

Dr. Venke Sankaran AFRL/RQ

NASA Ames Research Center

4 Dec 2012

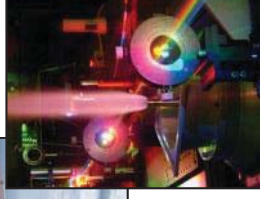
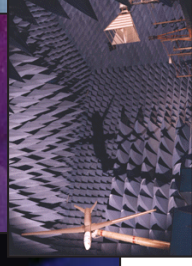
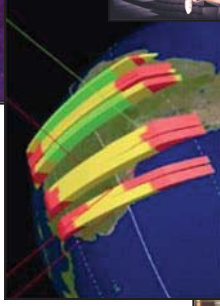
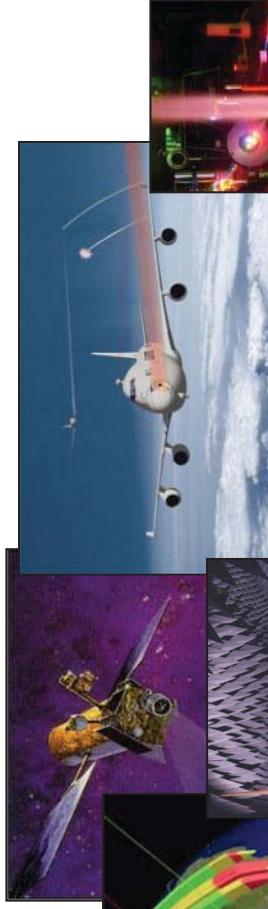
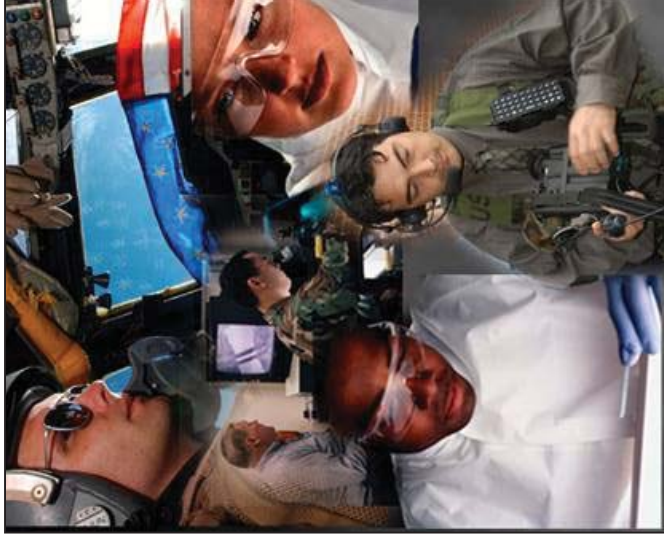
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Air Force Research Lab



Air Force Research Laboratory



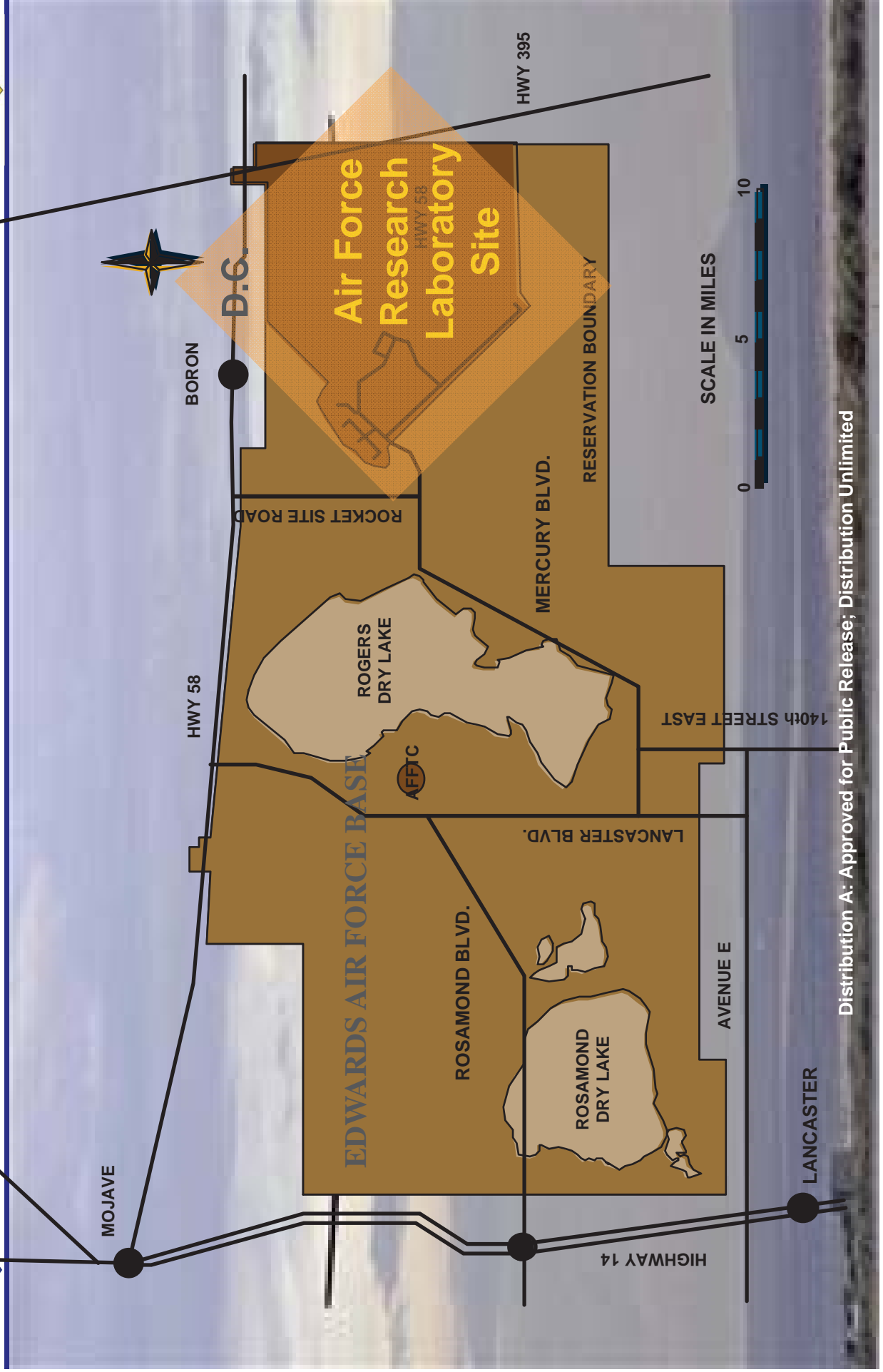
- 10 Major R&D sites across US
- 40 Locations around the World
- 10 Technical Directorates
 - Air Vehicles (RB)
 - Propulsion (RZ)
- Aerospace Systems Directorate (RQ)



- 5,400 Gov't Employees
- 3,800 On-site Contractors



Edwards Research Site





Facilities



Bench-level Labs



Altitude Facilities

- From micro-newtons to 50,000 lbs thrust



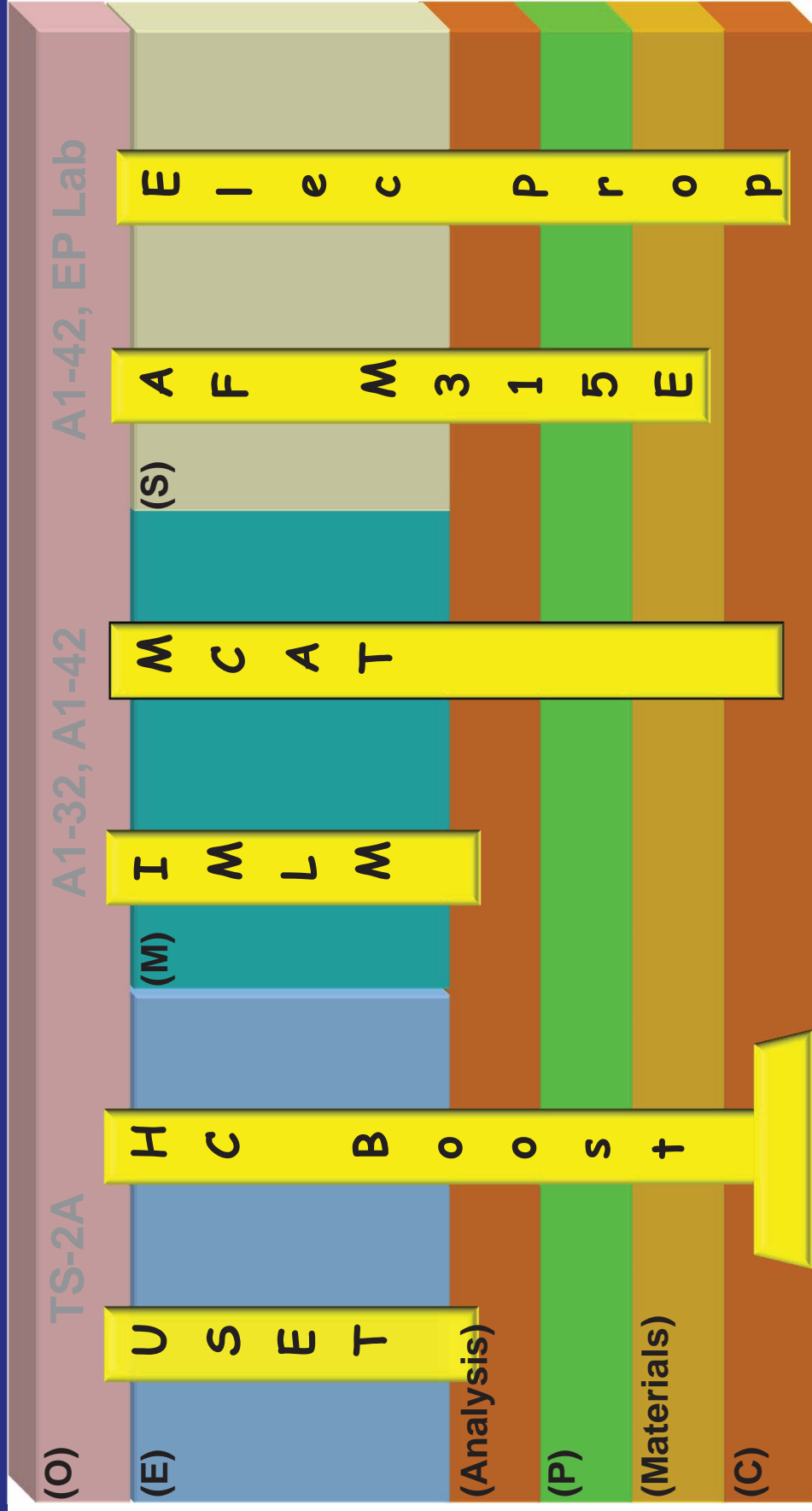
High Thrust Facilities

- 19 Liquid Engine stands, up to 8,000,000 lbs thrust
- 13 Solid Rocket Motor pads, up to 10,000,000 lbs thrust





Programs of Interest



USET – Upper Stage Engine Tech,
IMLM – Integrated Motor Life Management
MCAT – Material Component Applications Tech

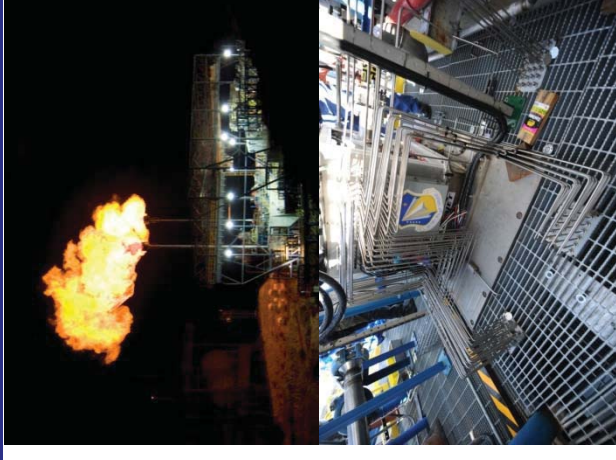
HC Boost – Hydrocarbon Boost
AFM 315E – Green Propellant,
EP – Electric Propulsion



USET

(Upper Stage Engine Technology Program)

- Validating new suite of LOx/Hydrogen rocket engine M&S tools through heavily-instrumented 4,000 hp, 90,000 rpm turbopump
- Risk reduction work ups TRL of components allowing SMC/LR NGE program to enter post-milestone B, saving years on the schedule and \$multi-M's in cost
- Verify and Validate suite of tools to greatly reduce the amount of physical testing by conducting better M&S during design to eliminate large amounts of testing
- NGE with SMC/LR and tools used in current NGE risk reduction work, Hydrocarbon Boost, >45 M&S tool-specific transitions to industry, DOD, NASA



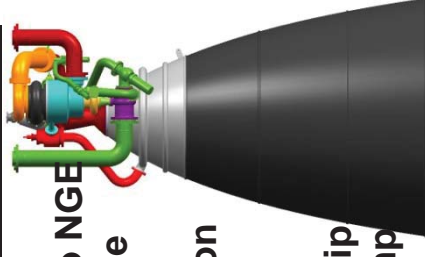
In-House:

- Test stand Buildup
 - Design of new facility hardware
 - Hardware Fabrication
 - Hardware Installation
- In-house tool validation and verification
- On-site rapid data reduction and analysis



The WOWs:

- SMC/LR requested TTP transition to NGE
 - Key member of AUSEP (Affordable Upper Stage Engine Program) IPT
 - Conducted Risk Reduction work on USET contract to support AUSEP TRL requirements
 - Most highly instrumented, highest tip speed and suction of any turbopump ever tested

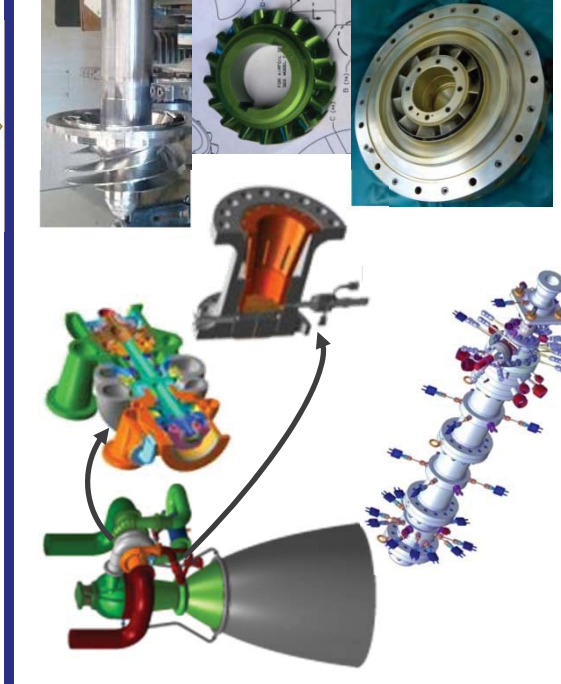


Program Completed, Report in Progress



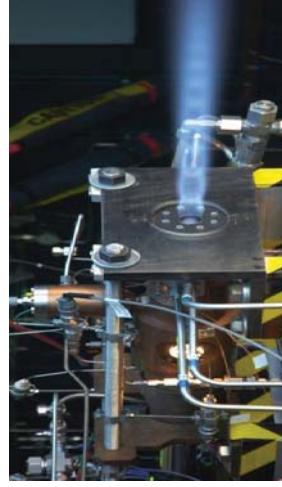
HC Boost (Hydrocarbon Boost Program)

- HCB establishes advanced, modern, domestic LRE Tech Base
 - 1st reusable high performance U.S. HC engine
 - Establishes Ox-rich staged combustion (ORSC) tech base for U.S.
 - Help sustain ailing U.S. rocket engine industry tech development base
 - HCB strongly supports SMC/LR American Kerosene Engine project



In-House:

- Building subscale test facility to mitigate combustion devices risk
- Critical combustion research using 219 funds
- Fuel thermal stability, nozzle cooling, injector design



The WOWs:

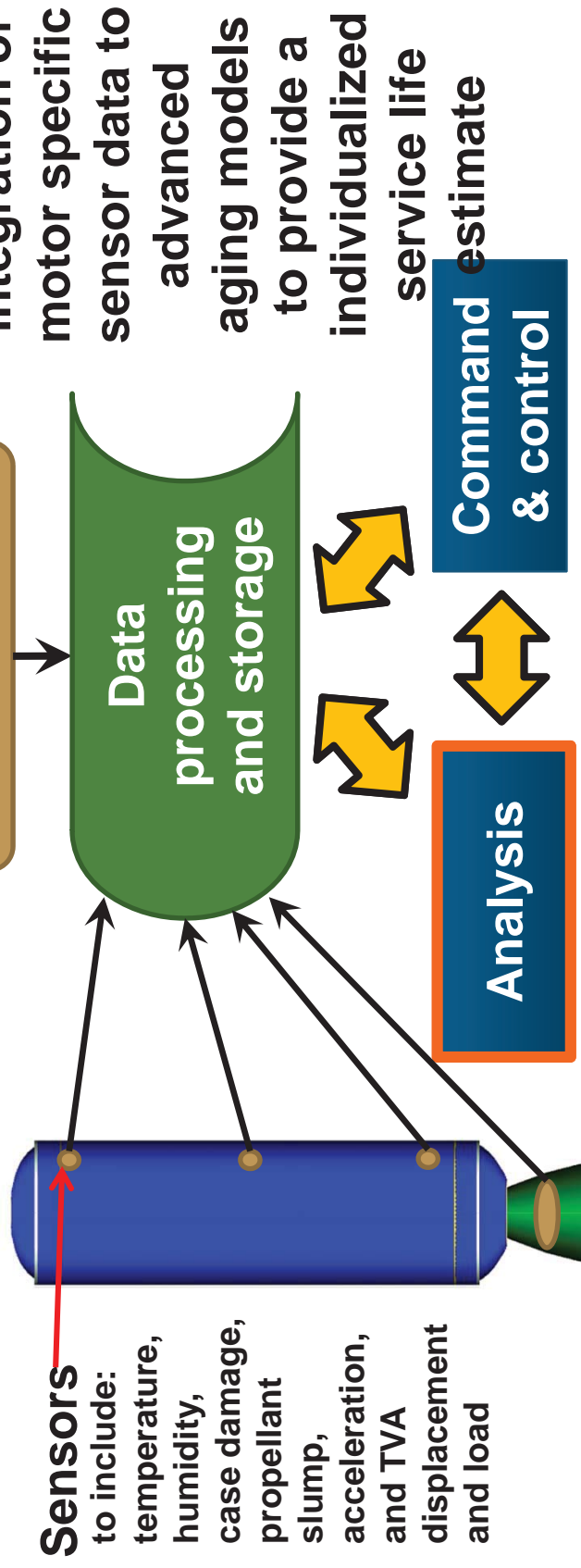
- Design, build, test ORSC LOx/Kerosene Liquid Rocket Engine Tech Demonstrator
- ORSC is a higher performing engine resulting in a smaller launch vehicle or an increase in delivered payload



IMLM

(Integrated Motor Life Management)

Goals: Reduce predictive uncertainty of future state of a motor on an individual basis by 20%/50% (near/far term goals)



In-House:

- Validation of A&S modeling capability
- AFNWC funded supported for ANDES improvement (Automated NDE Data Evaluation System)
- ICBM Program Office bringing A&S analysis capability in-house

The WOWs

- Potential to provide millions in cost avoidance
- Provide accurate near real-time motor health condition (diagnostics)
- Provide individualized service life estimates (prognostics)
- Transition opportunity ~ 2018



MCAT

(Motor Component Assessment Technology)

What are we doing? Developing new solid rocket motor (SRM) components and M&S that decrease inert weight by 20%.

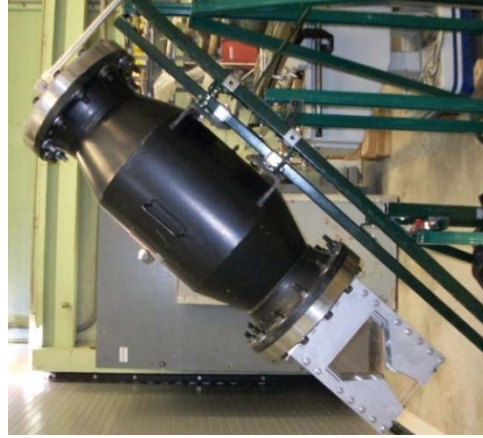
Customer why? High-speed penetrator weapons will enable attack of deeply-buried targets.

Tech Reason? New M&S tools may enable higher efficiencies from SRM designs.

Transition? 3 of 6 FY12 task orders support an AFRL FCC. 1 of 6 FY12 task orders supports

AFNWC In-House:

Experiments to validate new models



The WOWs

- The AFNWC propellant task is part of a plan that may save \$2.1B in future acquisition costs



Electric Propulsion

What are we doing? Developing new technologies that enable less expensive, more maneuverable and more agile s/c

Customer Why? Reducing launch mass substantially reduces launch cost, increases payload fraction, and enables missions otherwise not possible (e.g. AEHF)

Tech Reason? Plasma propulsion increases Isp by 10x, reducing s/c propellant 10x, enabling lighter and/or more capable s/c

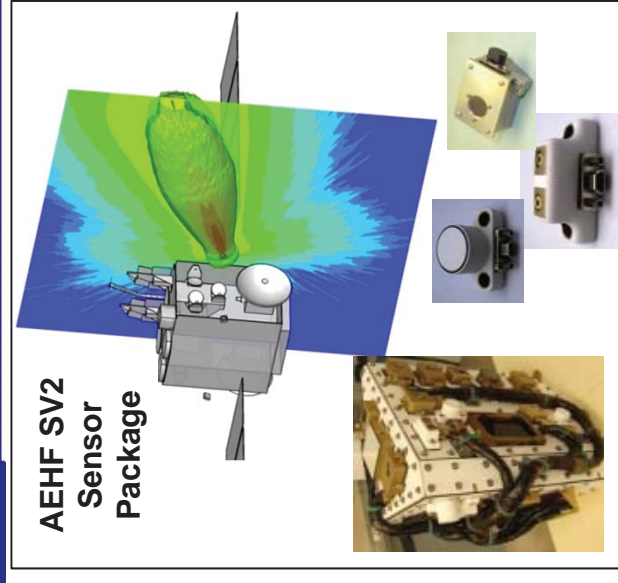
Transition?

- Tech demos: FalconSat-5—demonstrating low power propulsion and spacecraft impact

- Operational systems: AEHF—enabling high mass spacecraft directly supporting warfighter

In-House:

- Test facilities
 - 8 vacuum chambers
 - Thruster design
 - Diagnostics
 - Validation of M&S
- Mod/Sim Program
 - Dedicated staff
 - Advanced numerical methods



AEHF SV2
Sensor
Package

The WOWs:

- AEHF requested assistance with thruster performance verification; SV-2 onboard diagnostics package flying right now
- Developed propulsion module for FalconSat-5 tech demo, including spacecraft interaction diagnostics
- Cubesat EP propulsion module selected by 2 constellations for flight in 2014
- National M&S effort for EP coordinated by AFRL-RZSS





AFRL Developed Advanced Monopropellants

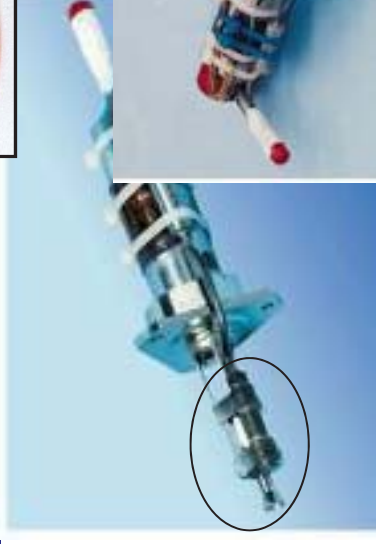


What are we doing? Providing advanced propellant with higher performance and much lower toxicity than hydrazine

Customer why? Faster operational response with reduced costs can be attained with greater mission capabilities

Tech Reason? Energetic ionic liquids provide low vapor toxicity and high energy density

Transition? Orbital flight experiment on TBD S/C-2014

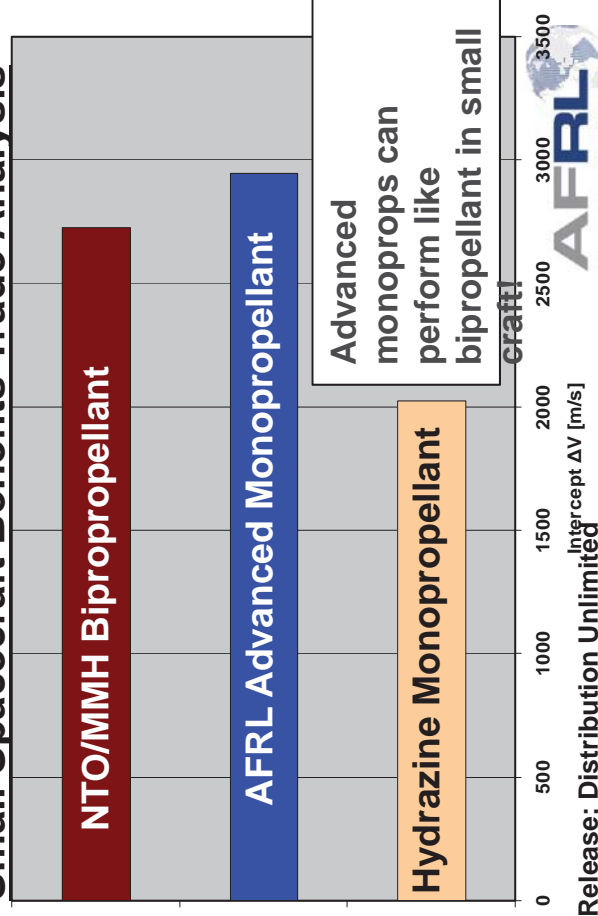


1N – 12N N_2H_4 Thrusters

In-House:

- Fully characterized small scale safety & hazard properties
 - Passes all safety requirements
 - DOT approval for transport
- First successful thruster firings
- Pilot scale propellant production
 - **Advanced monopropellant cost = hydrazine cost**
- Supplying transition programs

Small Spacecraft Benefits Trade Analysis



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Combustion Instability



Damaged F-1 engine injector faceplate
due to combustion instability

- Combustion instability occurs when the combustion dynamics couple with the combustion chamber acoustics
- Irreparable damage can occur in <1s
- Combustion instability caused a four year delay in the development of the F-1 engine used in the Apollo program
 - > 2000 full scale tests
 - > \$400 million for propellants alone (at 2010 prices)
- CI has been identified as a major risk factor in AFRL's Hydrocarbon Boost program.

“Combustion instabilities have been observed in almost every engine development effort, including even the most recent development programs” – JANNAF Stability Panel Draft (2010)



Rayleigh Criterion

$$\mathcal{R} = \frac{1}{t_f - t_0} \int_{t_0}^{t_f} \left(\frac{\int_{\Omega} (p(\vec{x}, t) - \bar{p}(\vec{x})) d\vec{x}}{\int_{\Omega} \bar{p}(\vec{x}) d\vec{x}} \right) \left(\frac{\int_{\Omega} (\dot{q}(\vec{x}, t) - \bar{\dot{q}}(\vec{x})) d\vec{x}}{\int_{\Omega} \bar{\dot{q}}(\vec{x}) d\vec{x}} \right) dt$$

- **Stated by Lord Rayleigh in 1878**

- Defines phase relationship between pressure and heat release
 - A positive value indicates that they are in phase and are driving the instability
 - A negative value indicates that they are out-of-phase and are damping the instability

- **Coupling relationship is very complicated**

- Controlled by acoustic interactions with sub-processes like injection, atomization, vaporization, mixing and combustion



High Pressures

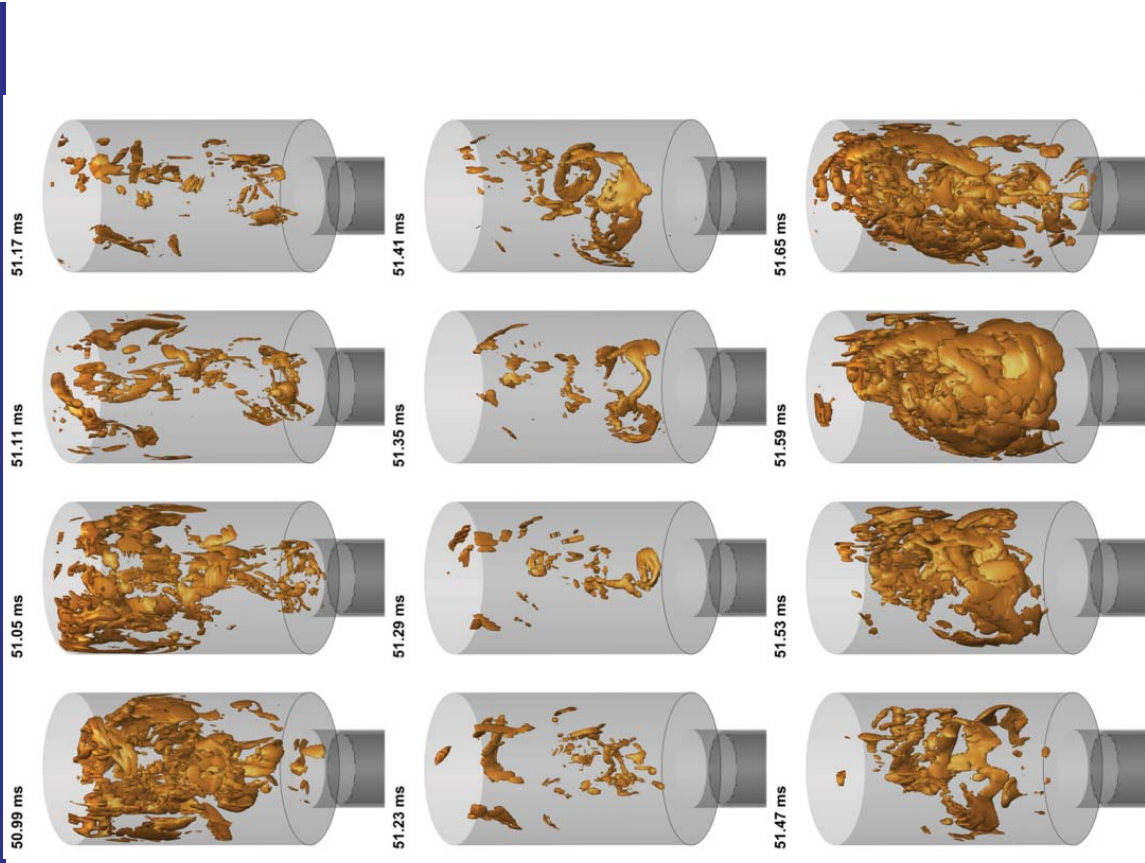
- **Rocket Conditions**
 - Very high pressures 1000-3000 psi
 - Cryogenic propellants at sub-critical temperatures
- **Diagnostics**
 - Extremely challenging to obtain detailed data in rocket environments
- **Modeling Challenges**
 - Multiphase phenomena
 - Extremely high density ratios
 - Wide range of velocity scales





Turbulence and Combustion

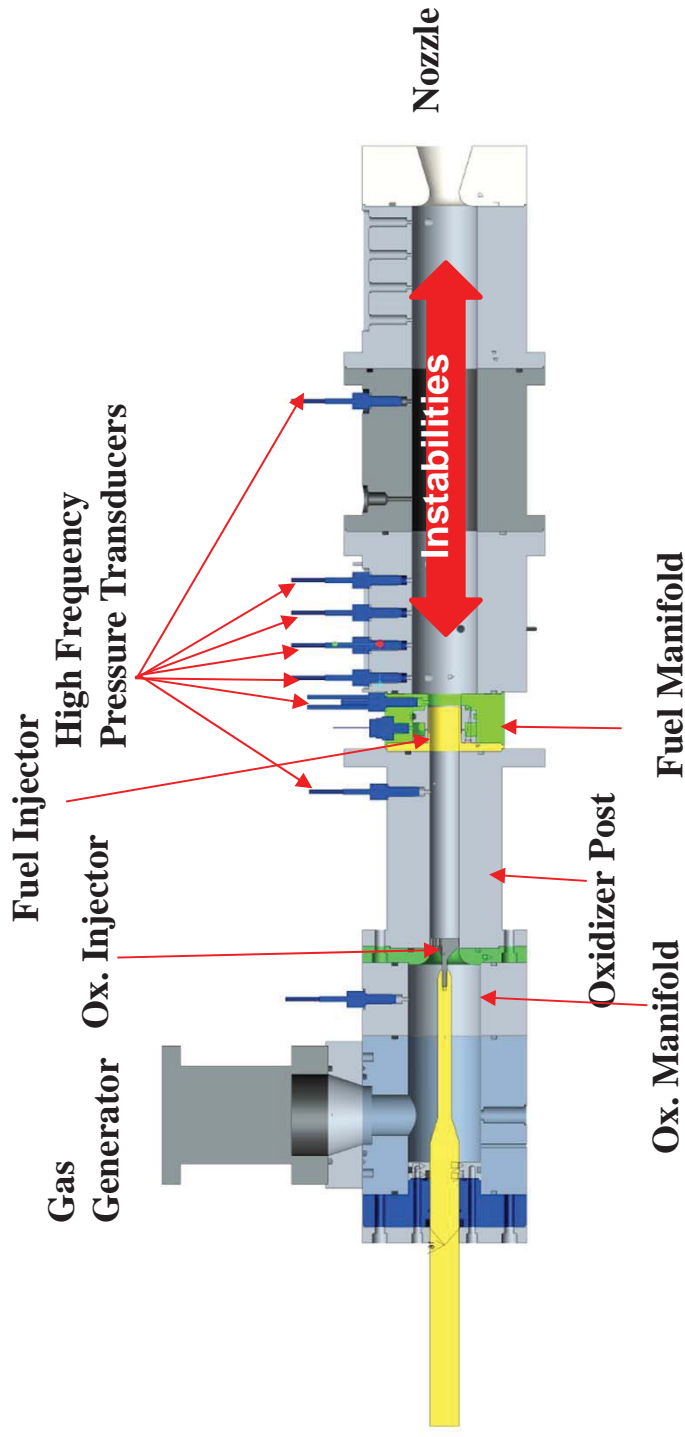
- **Turbulence**
 - Unsteady dynamics requires LES or RANS/LES
- **Chemistry**
 - Detailed chemical mechanisms for typical hydrocarbon fuels
- **Turbulent-Chemistry Interactions**
 - Sub-grid chemistry source term closure





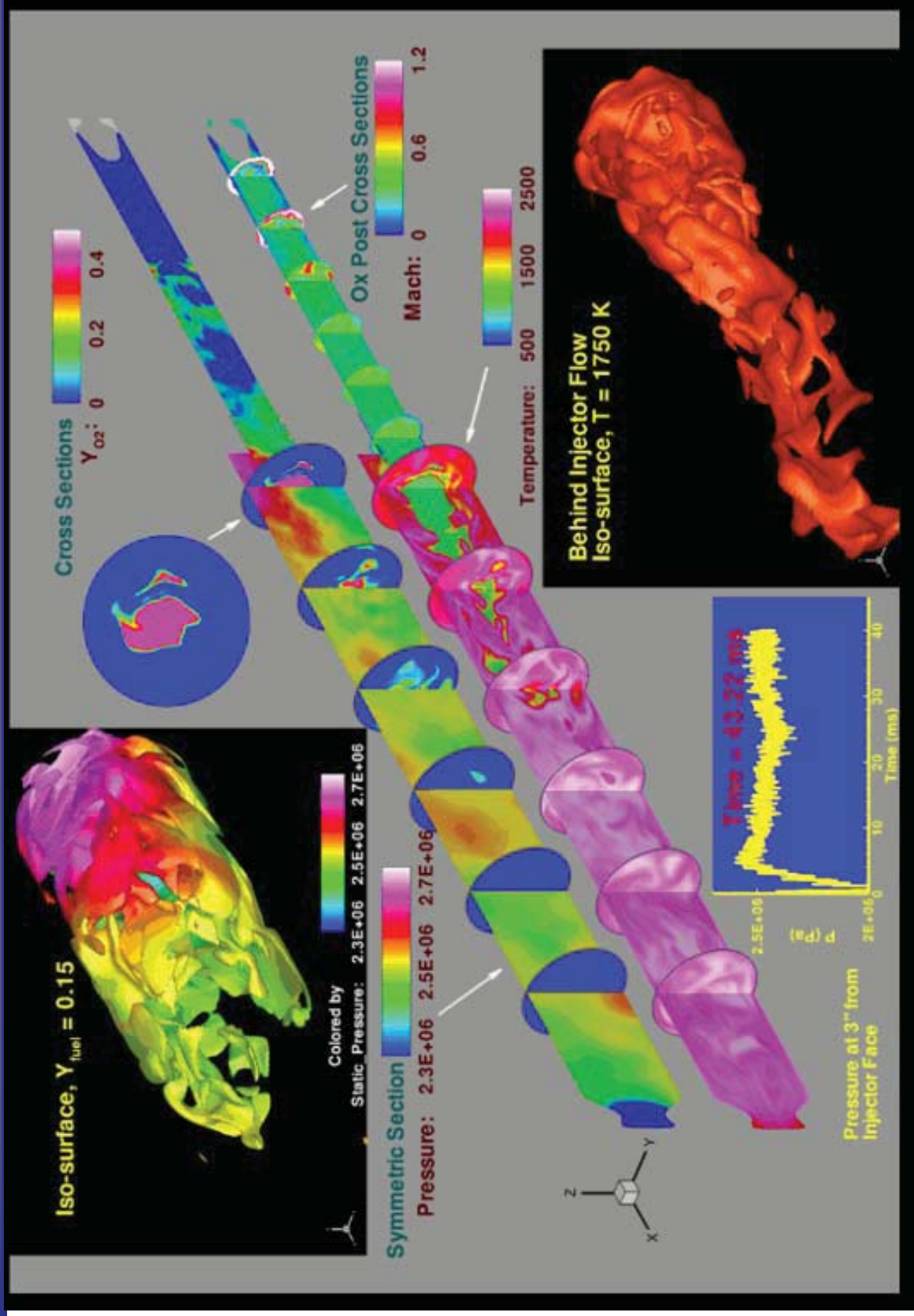
Boundary Conditions

- **Acoustic Coupling**
 - Chamber acoustics couple with oxidizer post and oxidizer and fuel manifolds
 - Need to include full configuration!





Data Processing





ALREST



Advanced Liquid Rocket Engine Stability Technology

• OBJECTIVE

- Develop advanced physics-based combustion stability design tools to reduce the risk of developing combustion instabilities in future Air Force liquid rocket engine development programs

• APPROACH

- Conduct data-centric, multi-fidelity model development in coordination with other national efforts



Data-Centric Model Development



Anderson (Purdue)

- AFOSR
- NASA CUIP
- **ALREST**
- AFRL

Frederick (UAH)

- NASA CUIP
- AFRL
- **ALREST**

Karagozian (UCLA)

- AFOSR

Leyva, Talley (AFRL)

- AFOSR
- **ALREST**

Cavitt (Orbitec)

- AFRL
- **ALREST**

Santoro (PA State)

- AFOSR (core)
- NASA CUIP
- **ALREST**

Yu (Maryland)

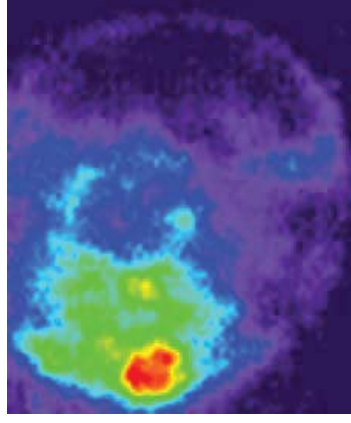
- NASA CUIP
- Zinn (GA Tech)
- AFOSR

Nestleroad Engin'ng

- MDA

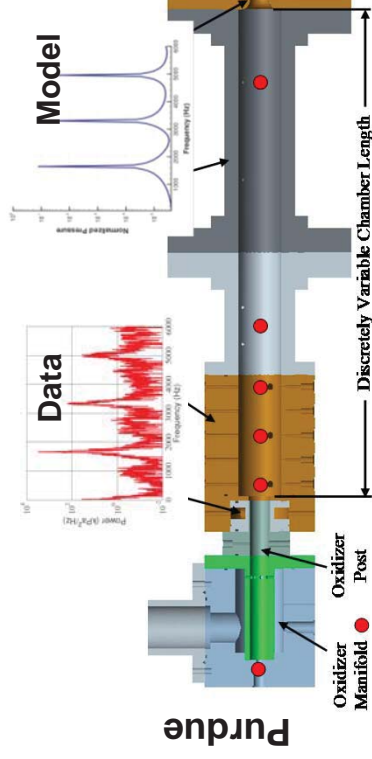
Experiments

Spinning CI

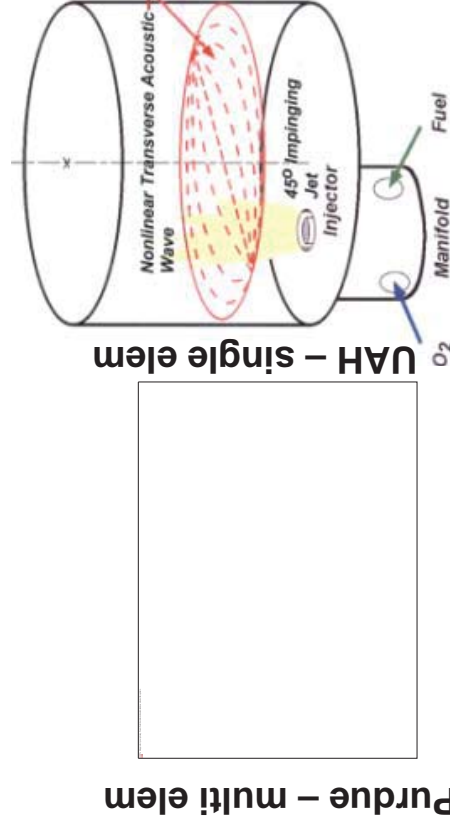


GA Tech

Longitudinal CI



Standing CI

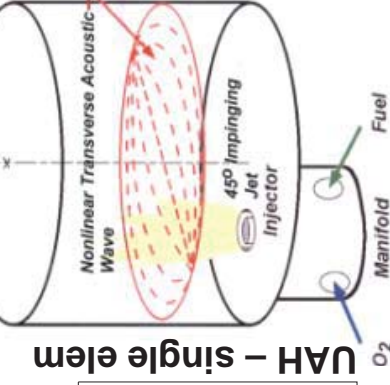


Purdue - multi elem

Driven jets



AFRL - coax



UAH - single elem

U. Maryland - 2D

Acoustics

HCB will be heavily instrumented to provide CI data

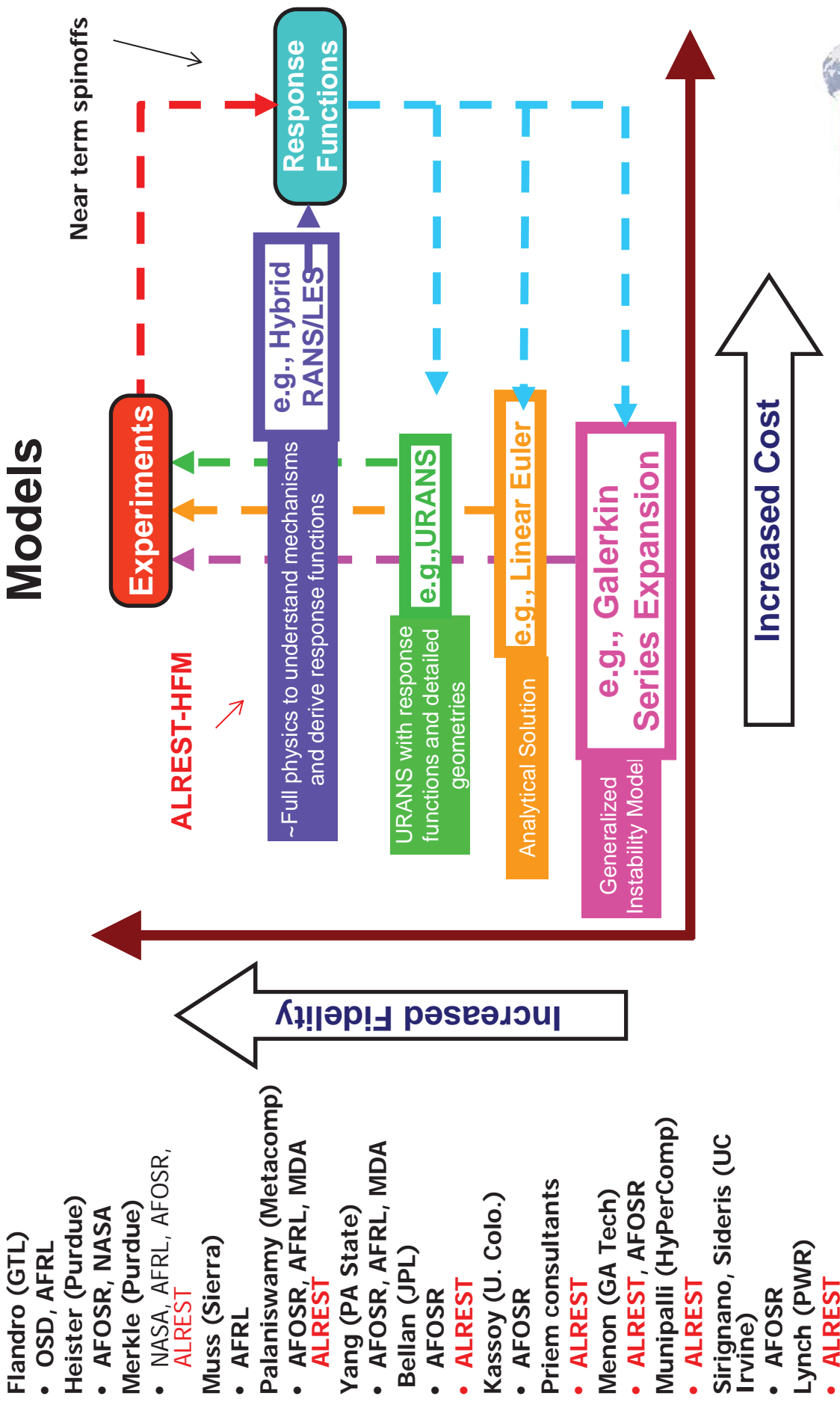
Full Scale (existing and HCB)

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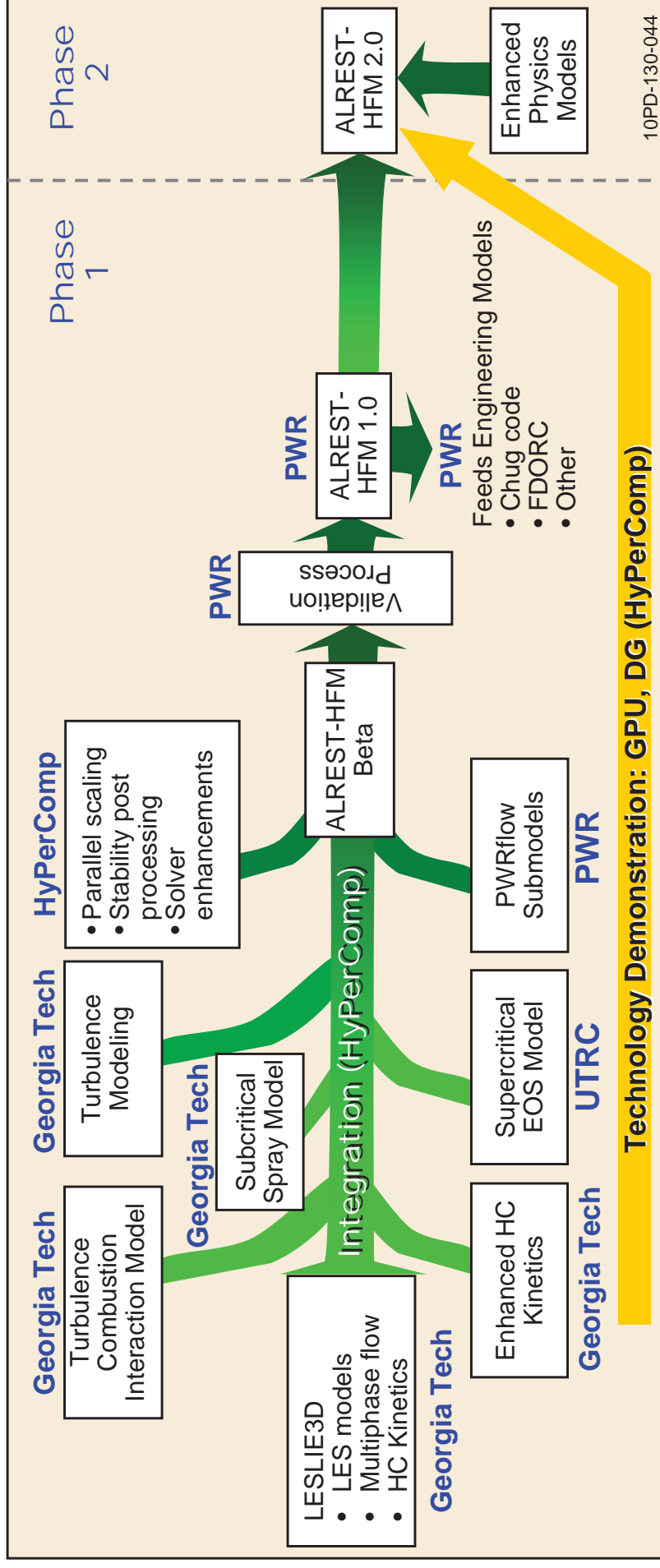


Multi-Fidelity Model Development





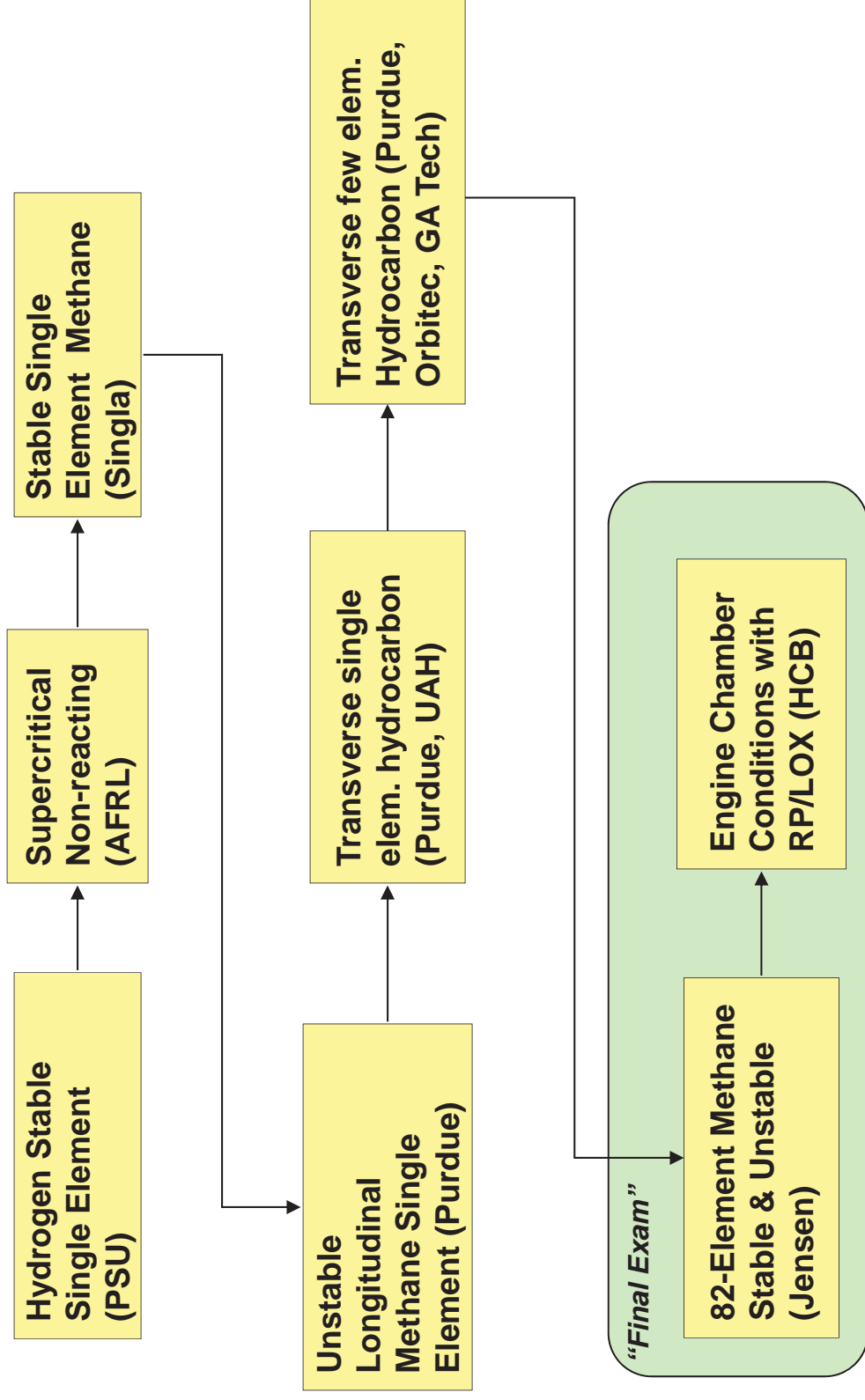
Approach



**Source code will be delivered and maintained
by Hypercomp after the contract ends**



ALREST Validation Cases

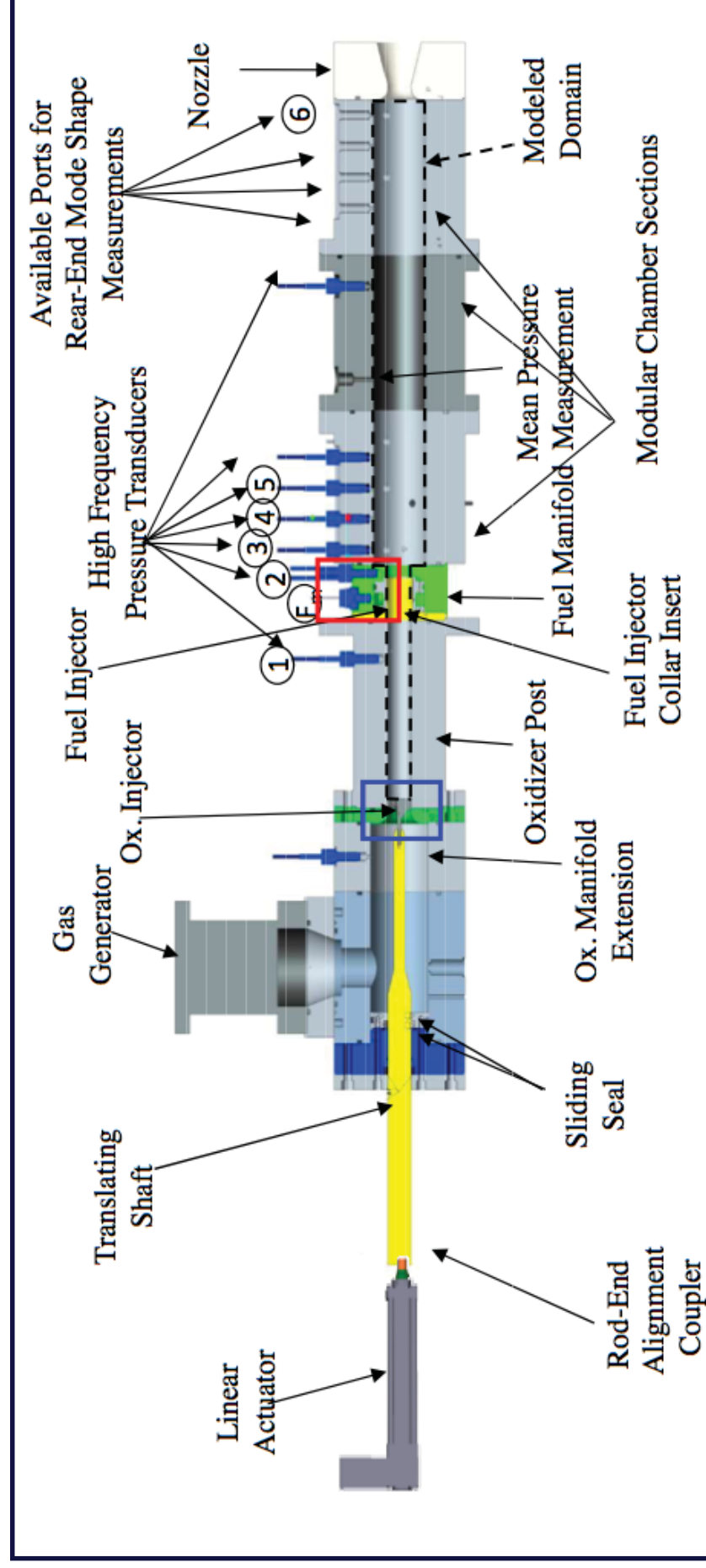




Longitudinal Stability Chamber



Purdue's Continuously Varying Resonance Chamber

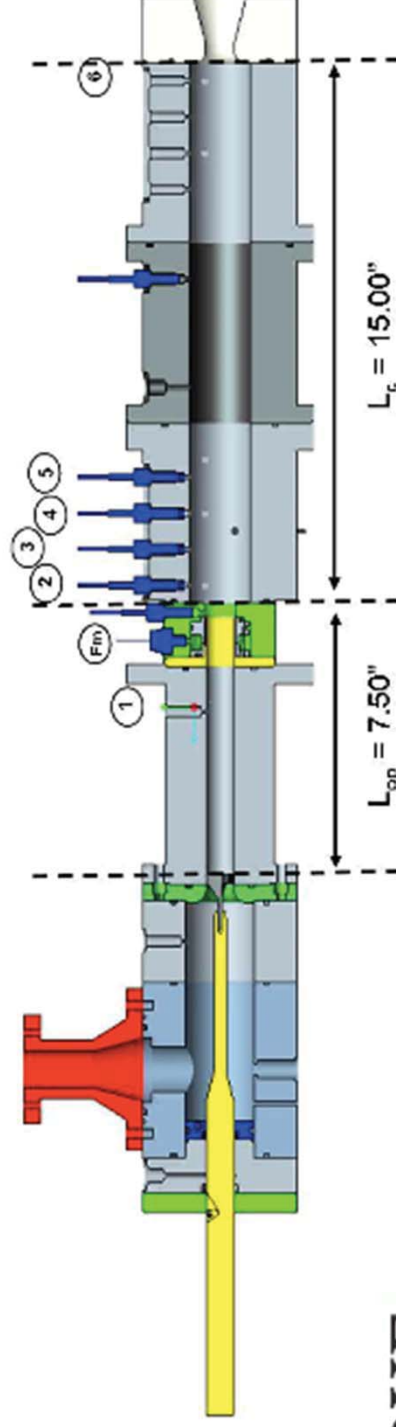
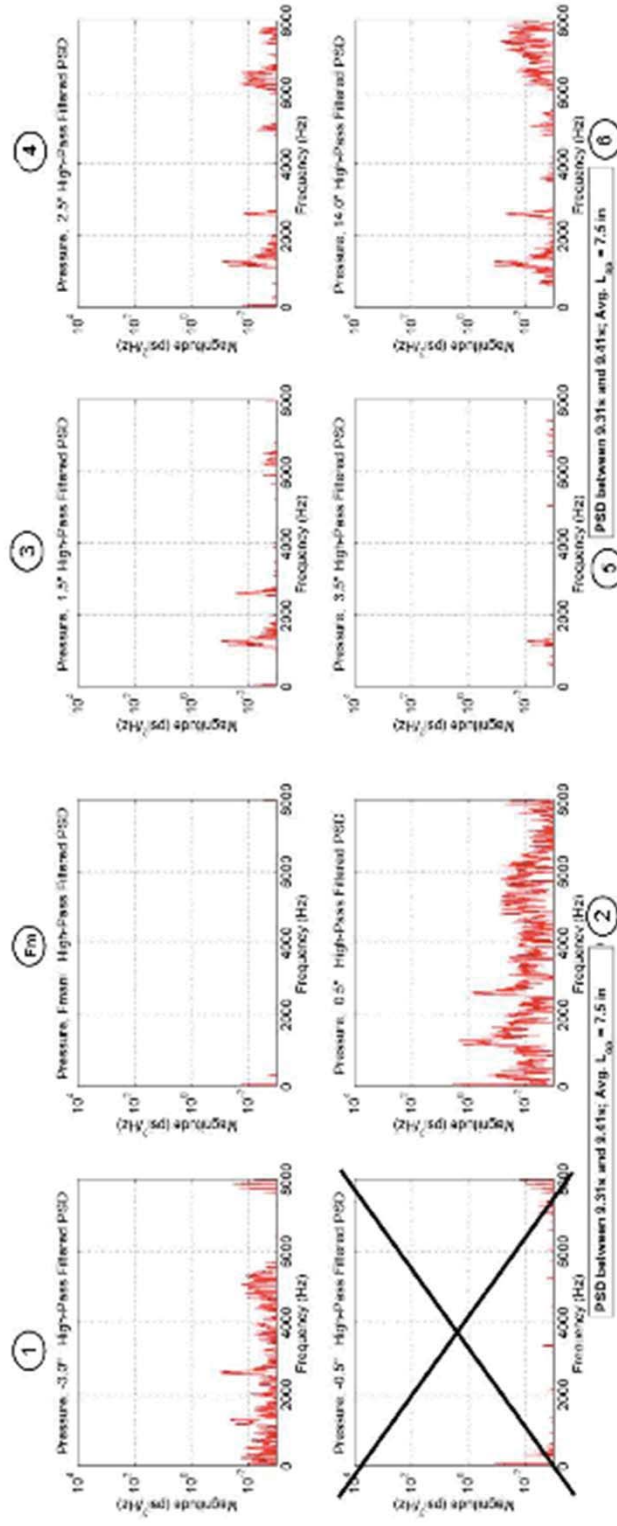




Sample Experimental Results

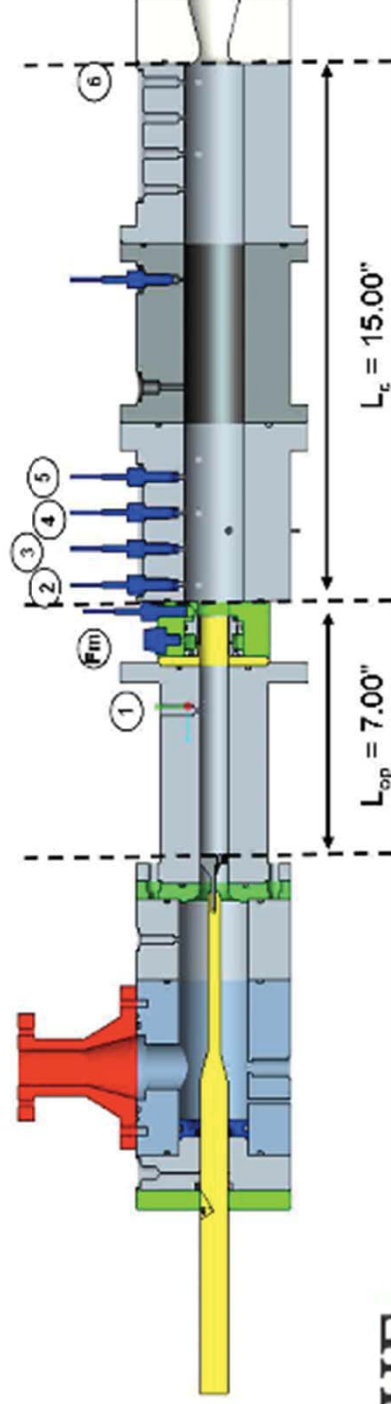
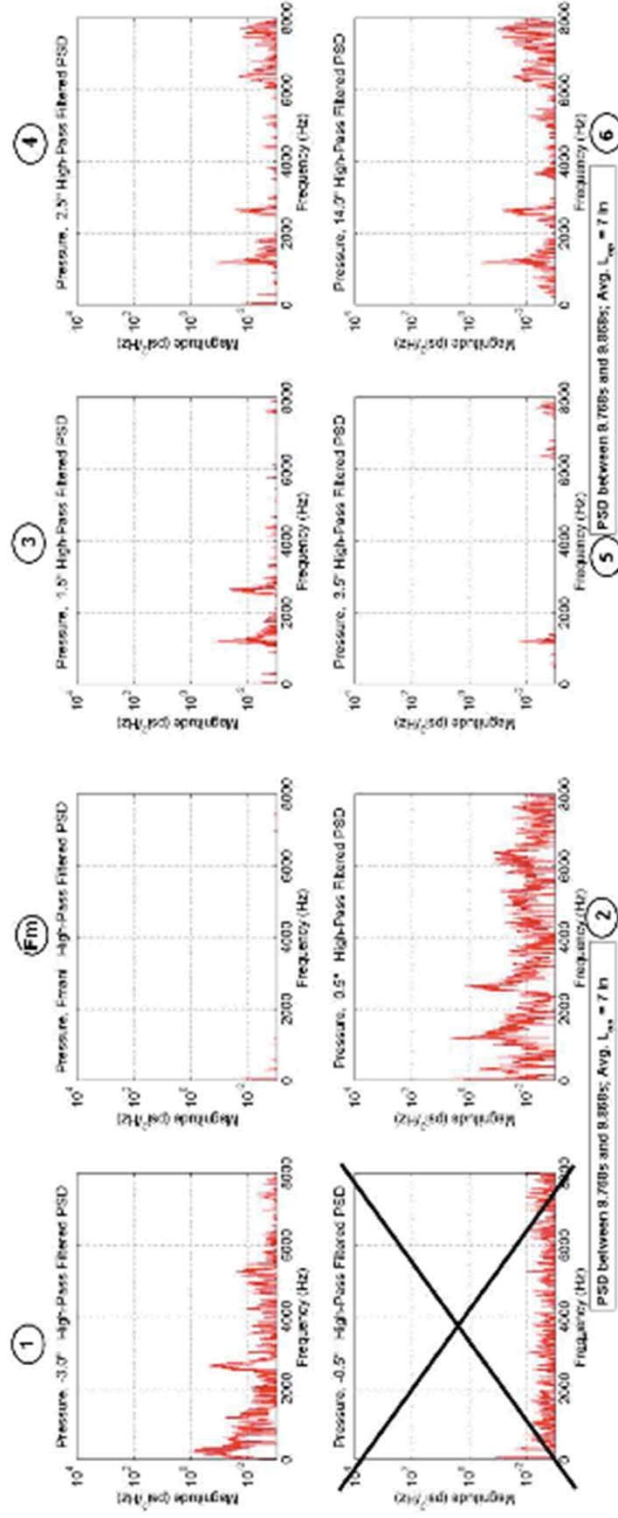


Experimental Results – PSD



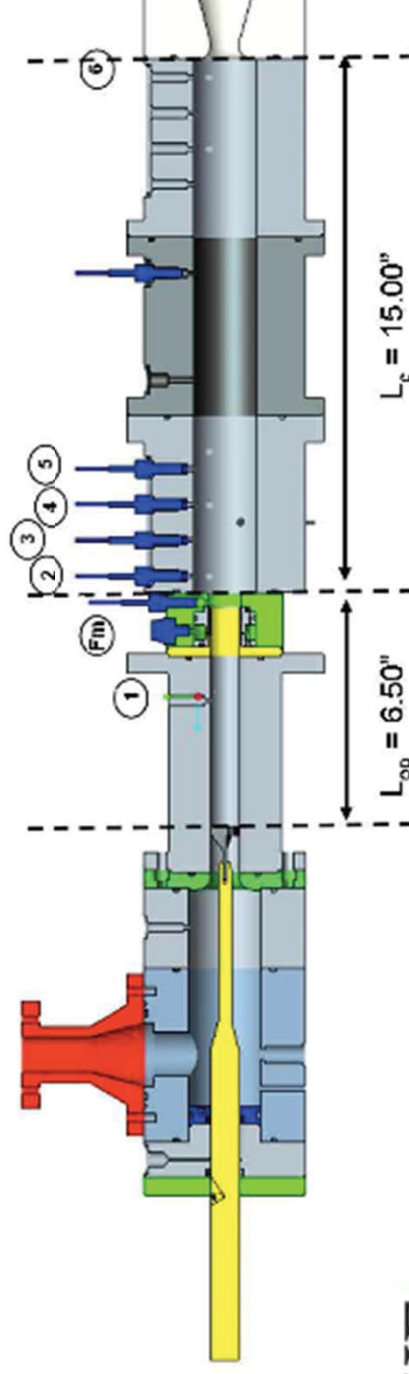
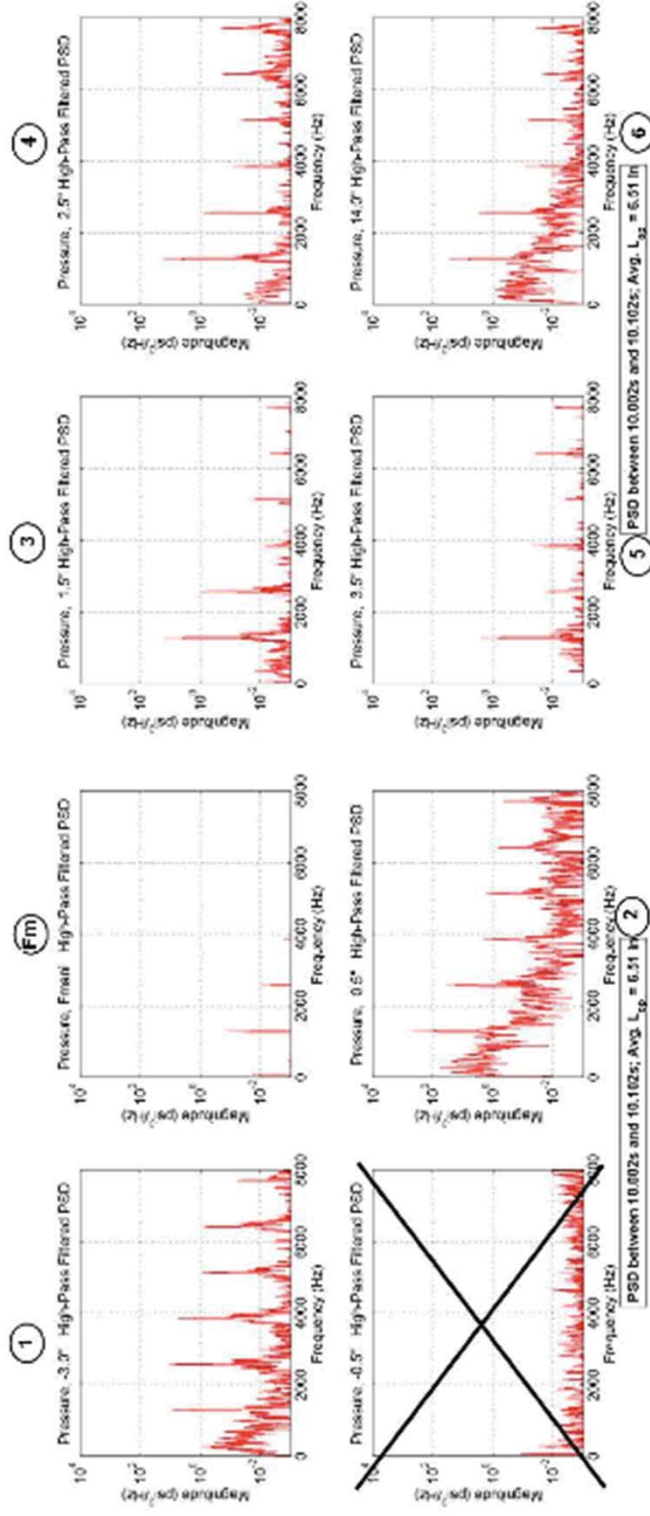


Sample Experimental Results



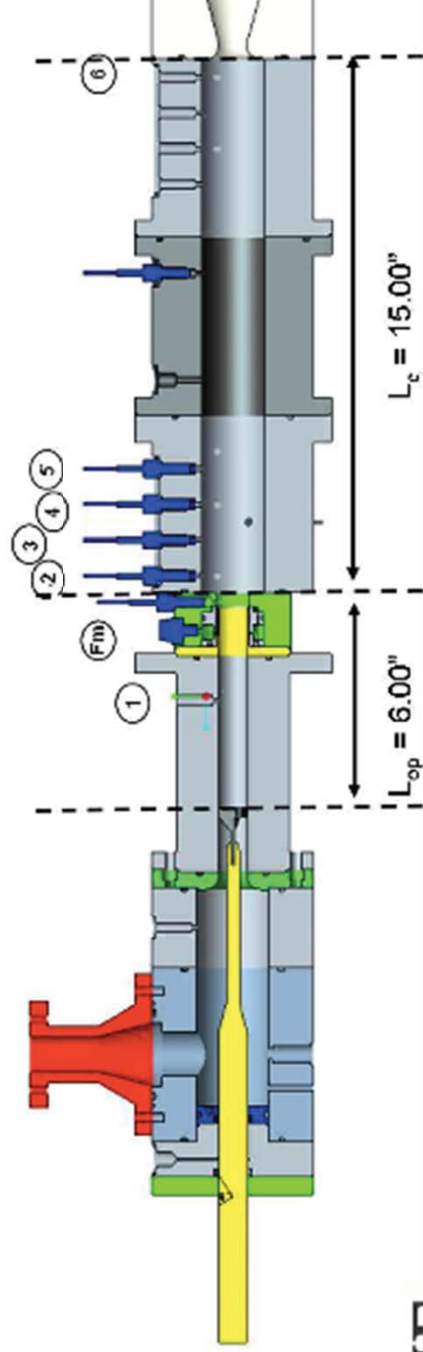
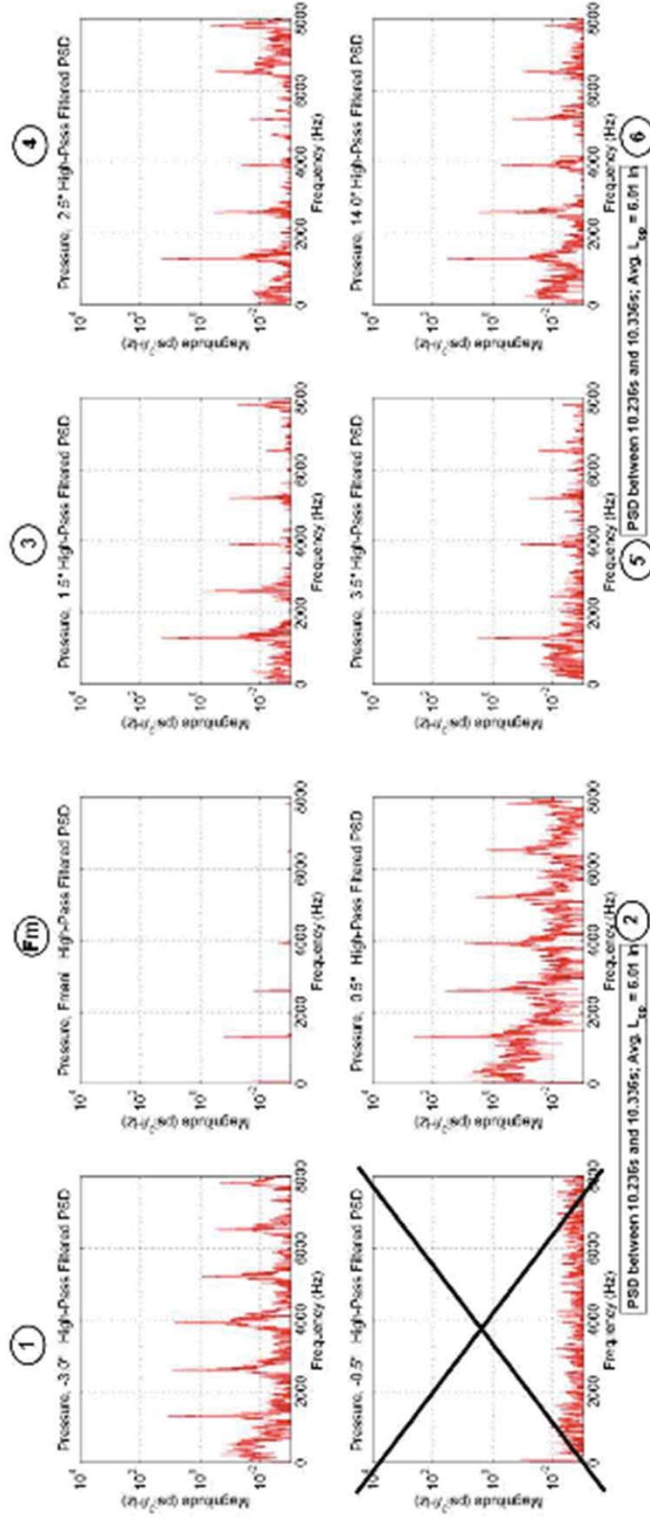


Sample Experimental Results



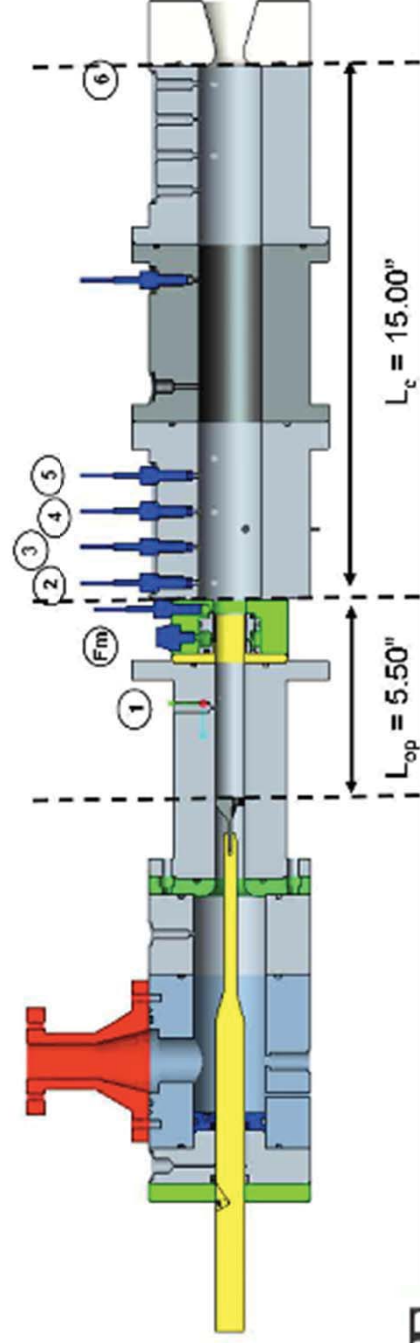
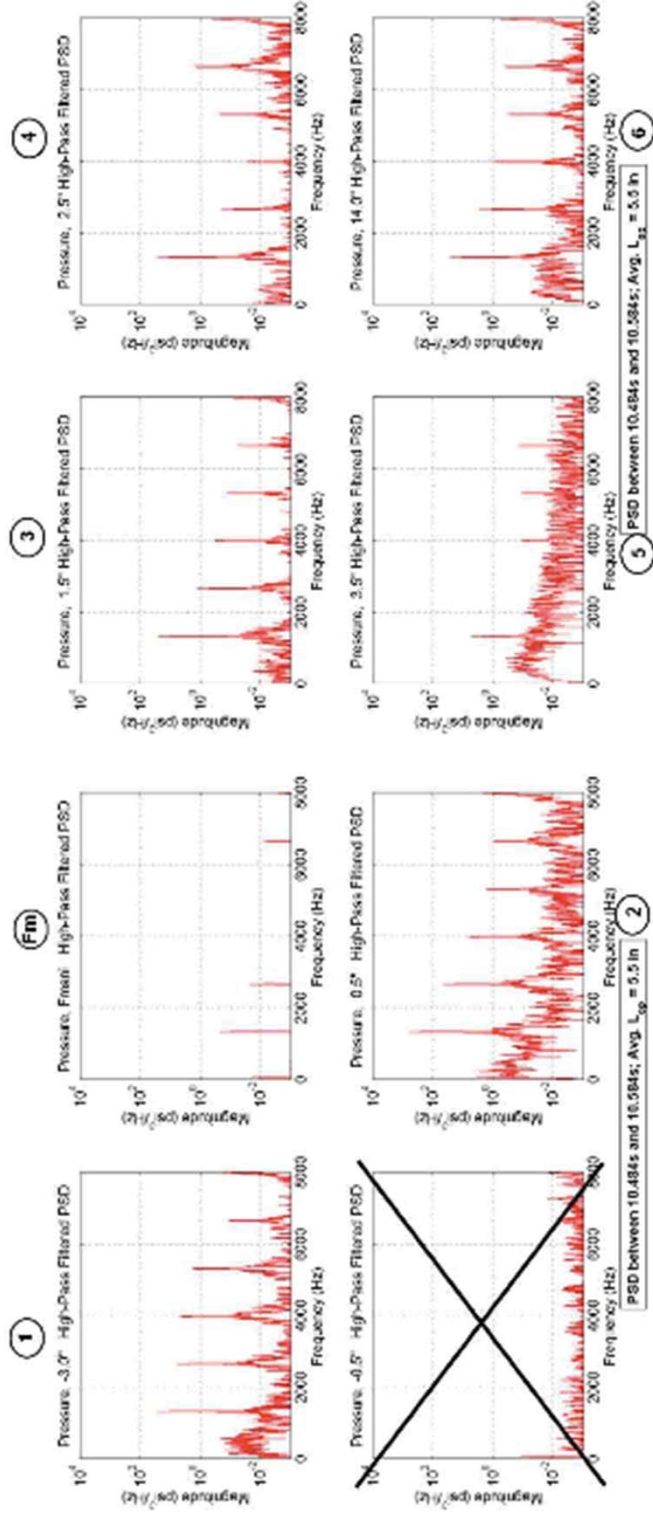


Sample Experimental Results



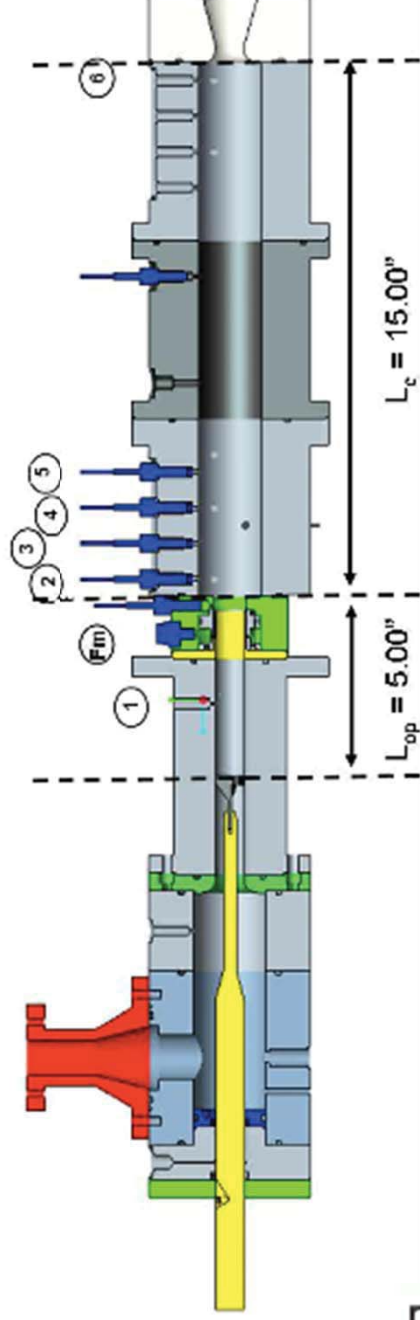
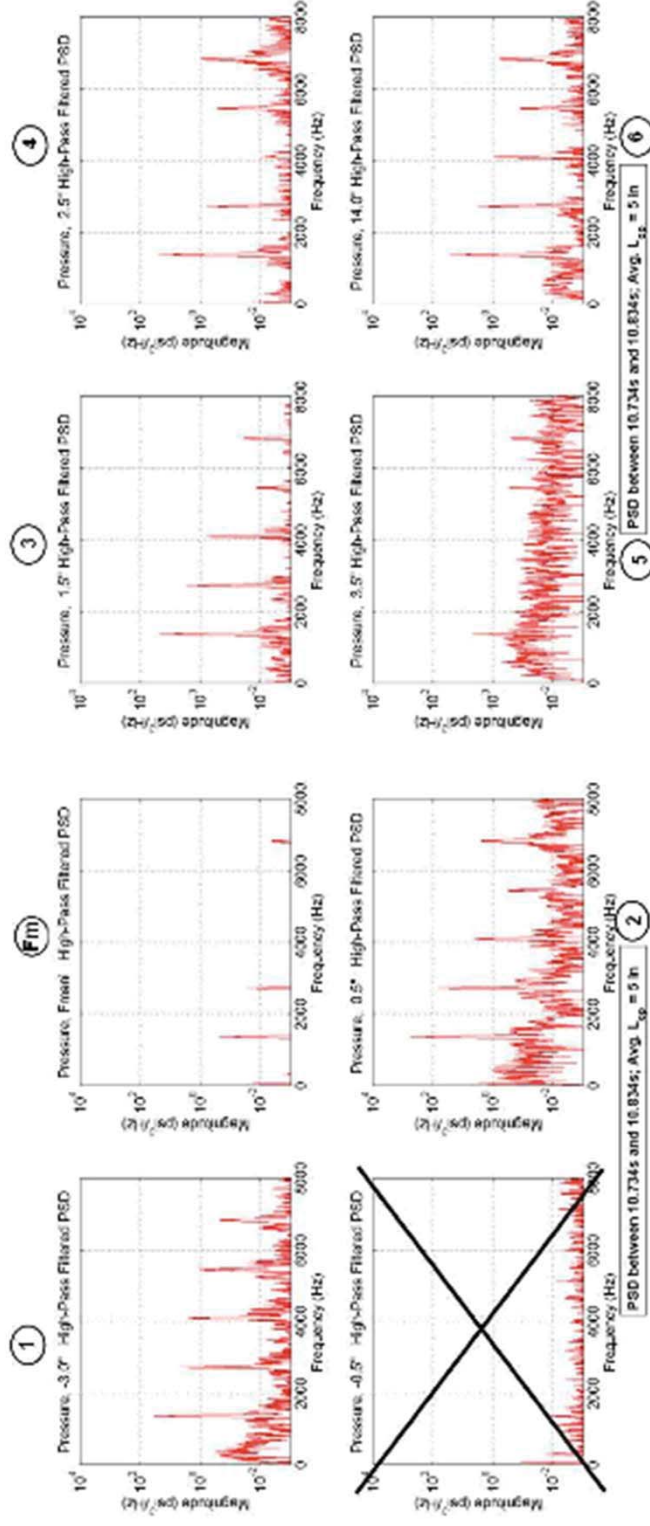


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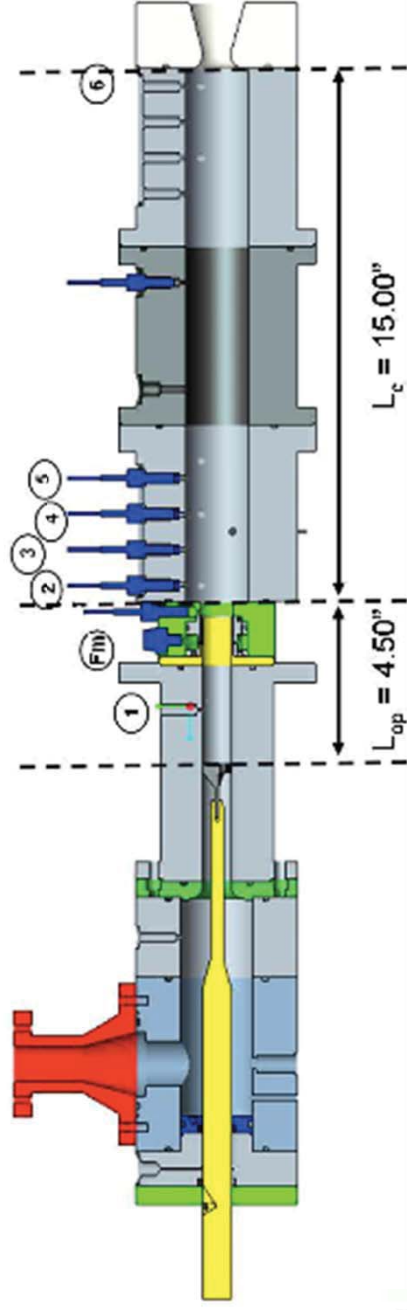
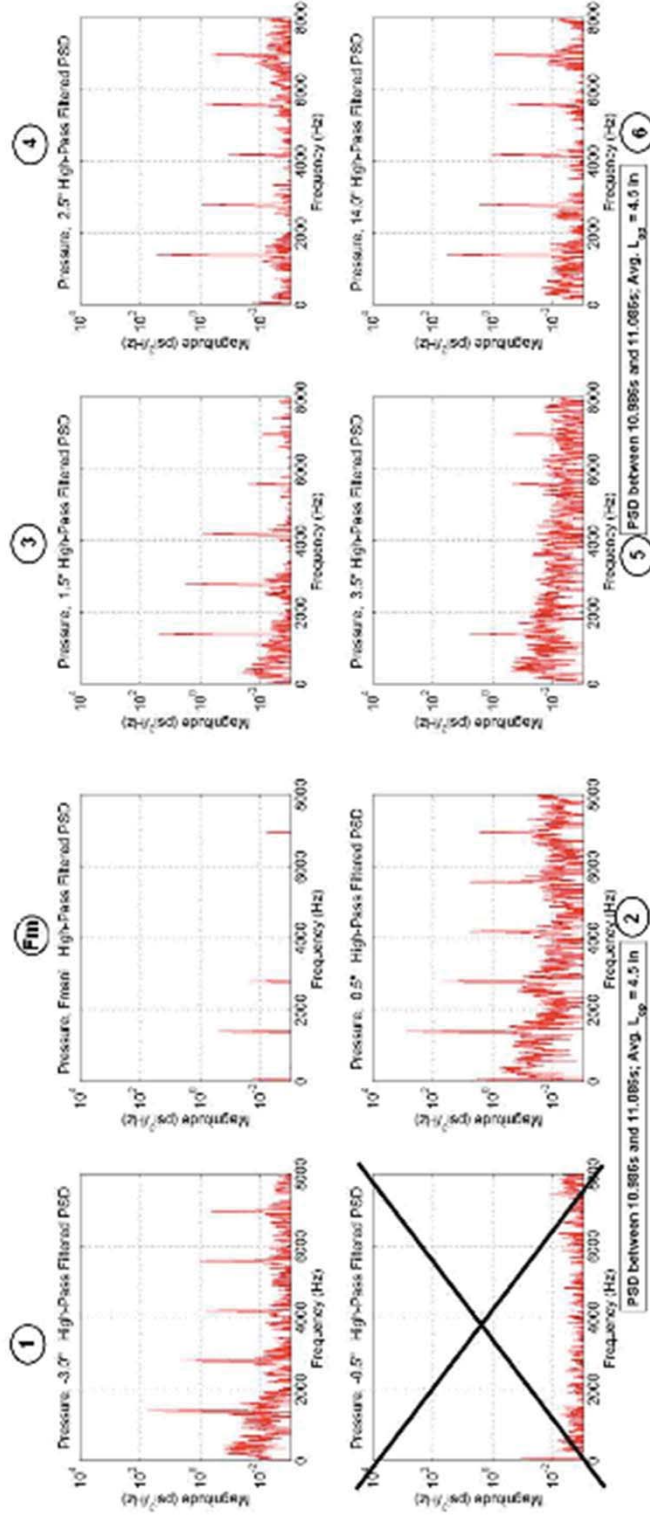


Sample Experimental Results



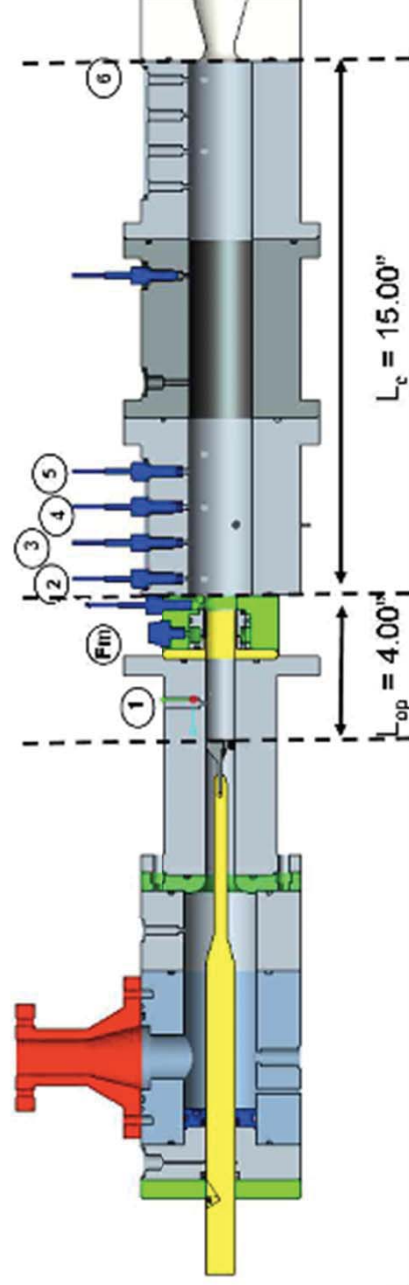
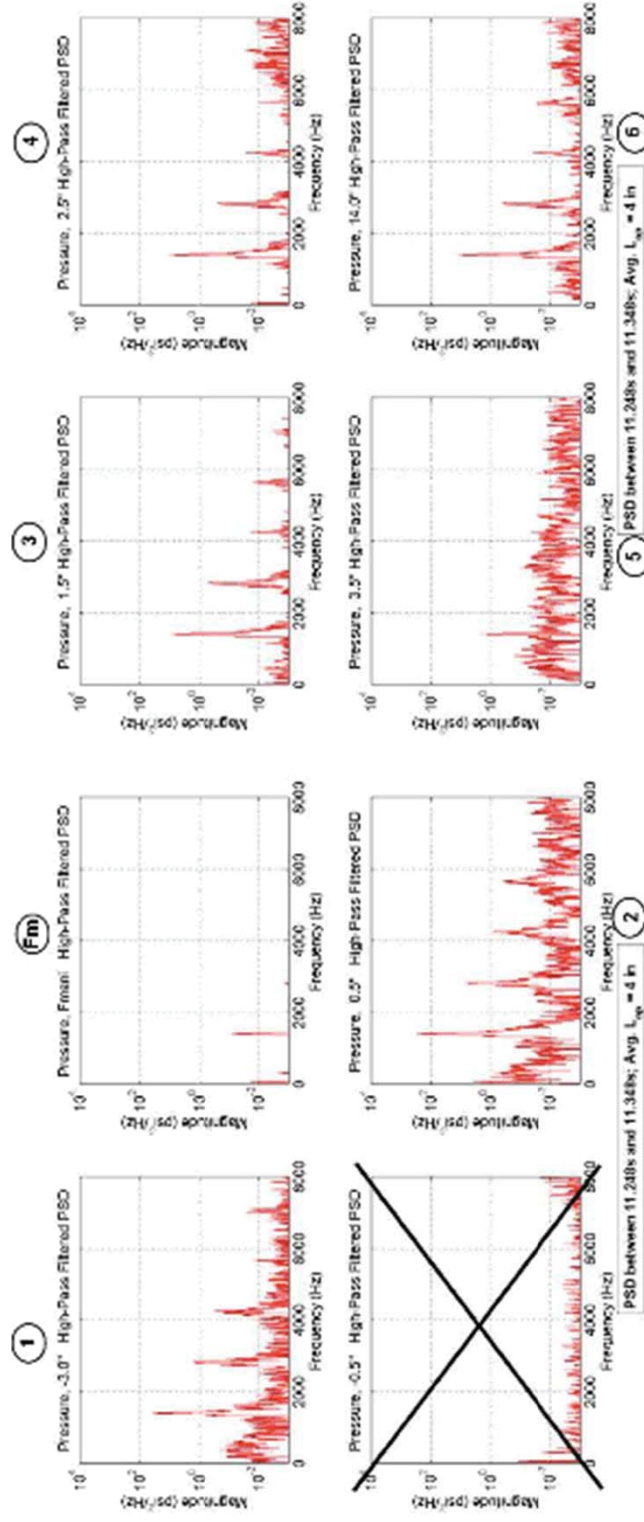


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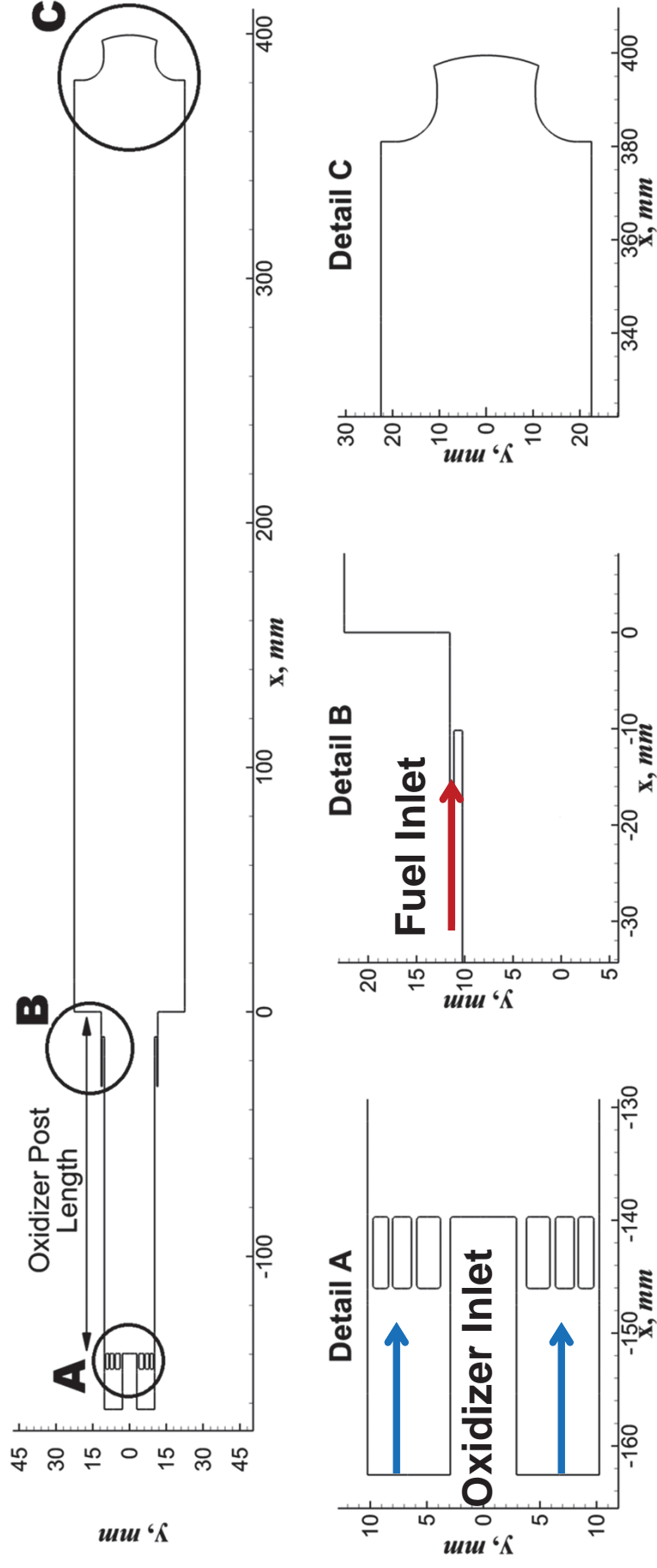


Sample Experimental Results





Computational Domain





Computational Results



Mach Number

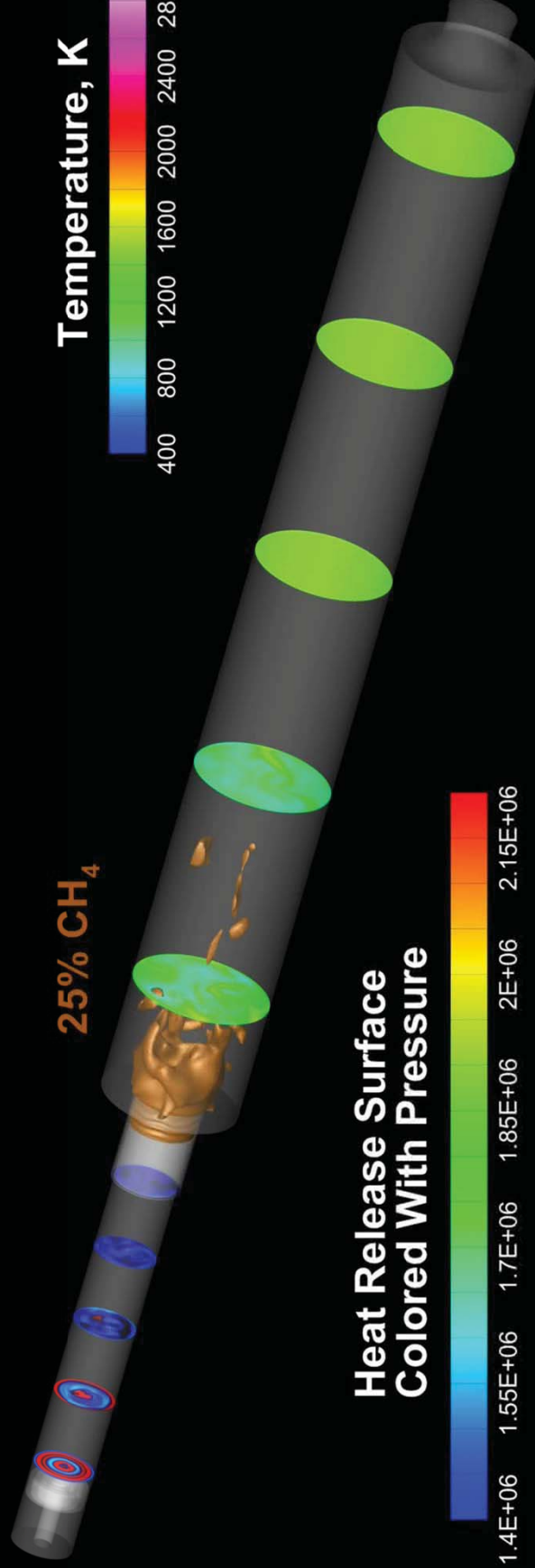


25% CH₄

Temperature, K

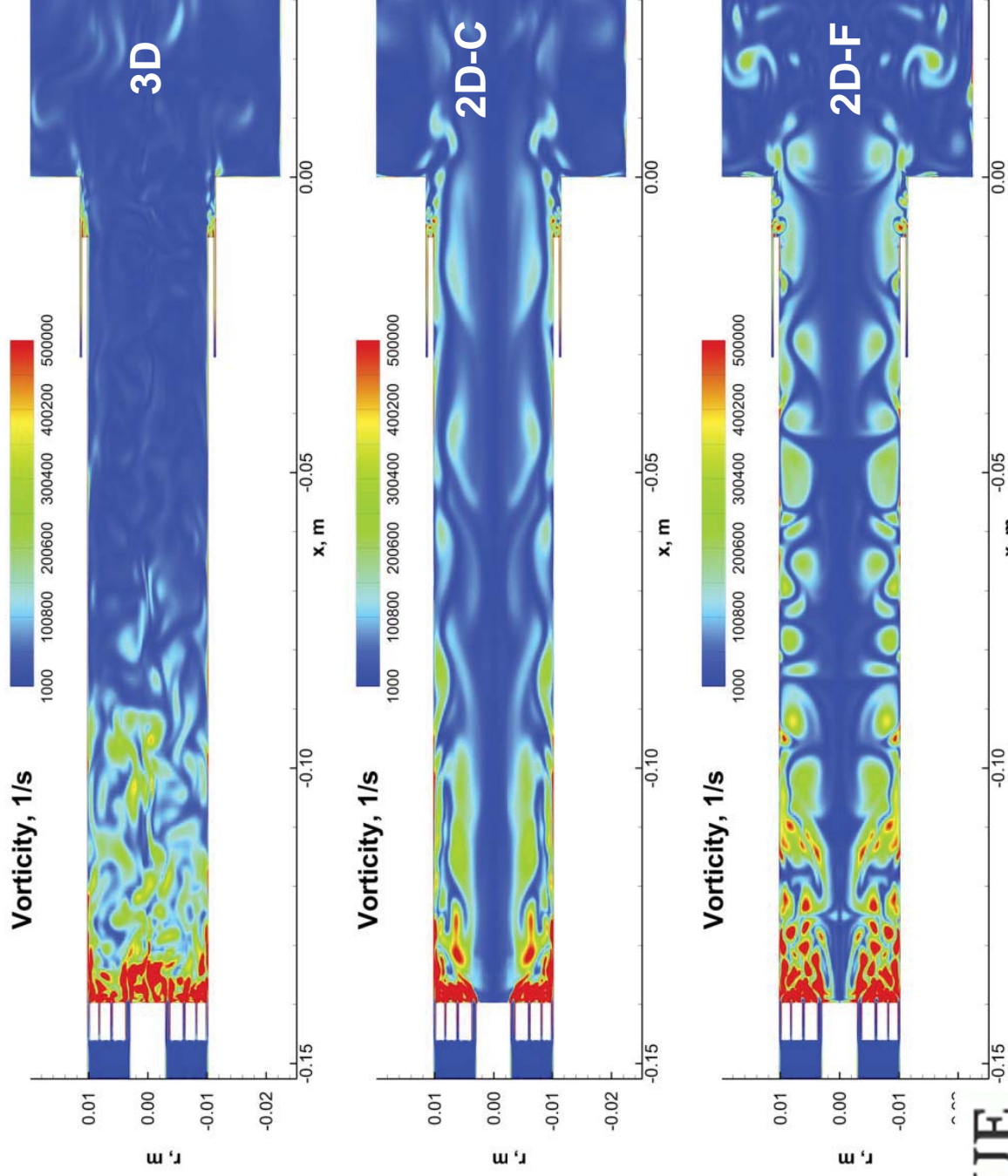


**Heat Release Surface
Colored With Pressure**





Vorticity

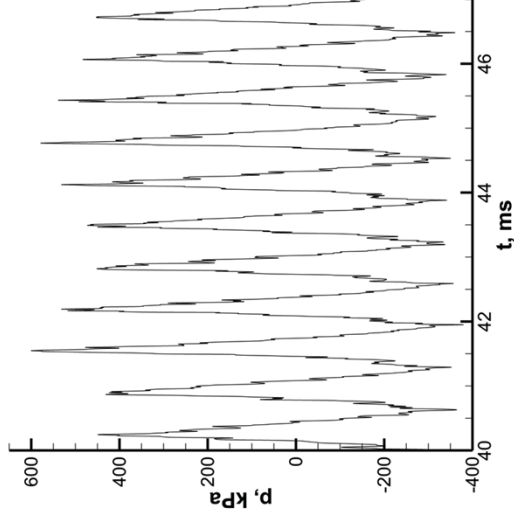




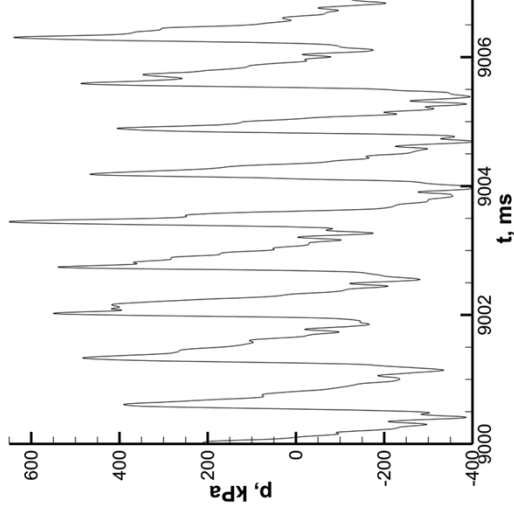
Pressure Waves



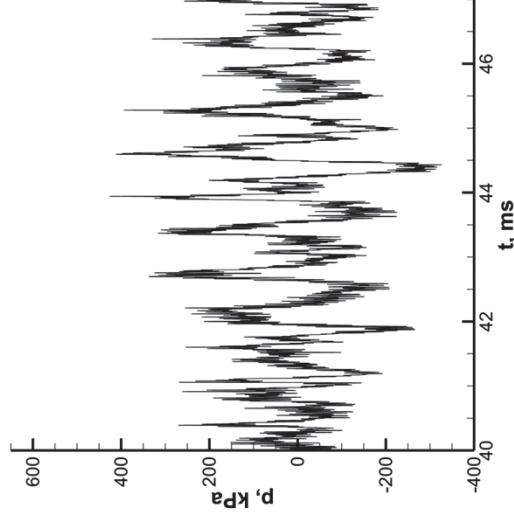
3D Pressure Signal



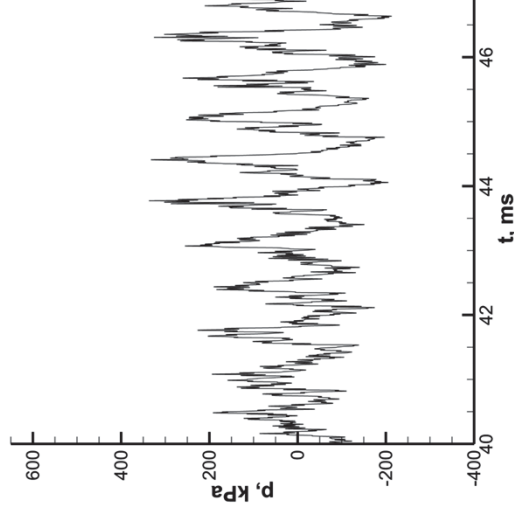
Experiment



2D - Fine Pressure Signal

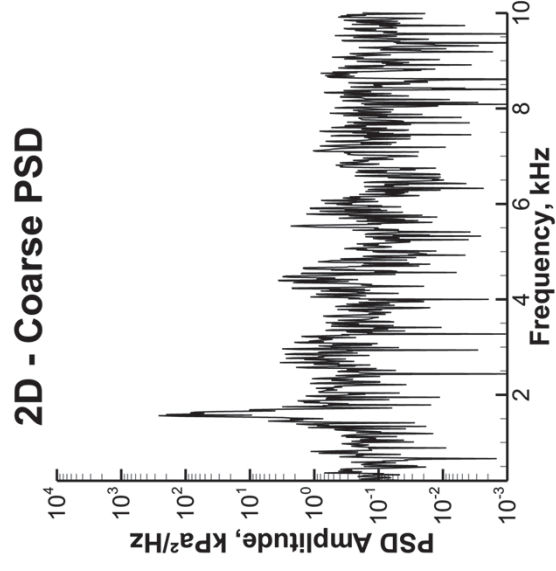
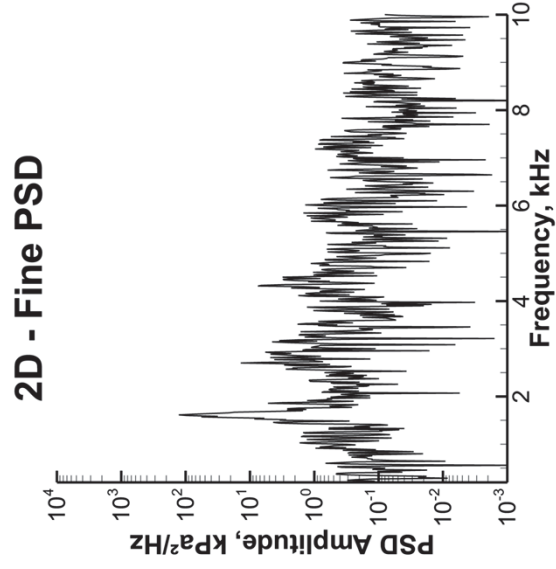
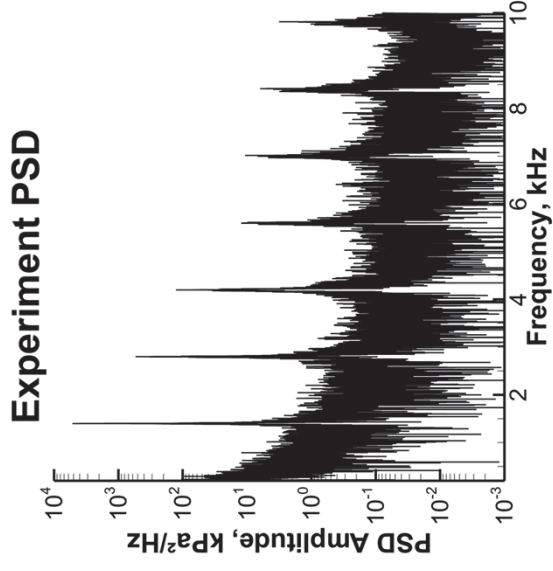
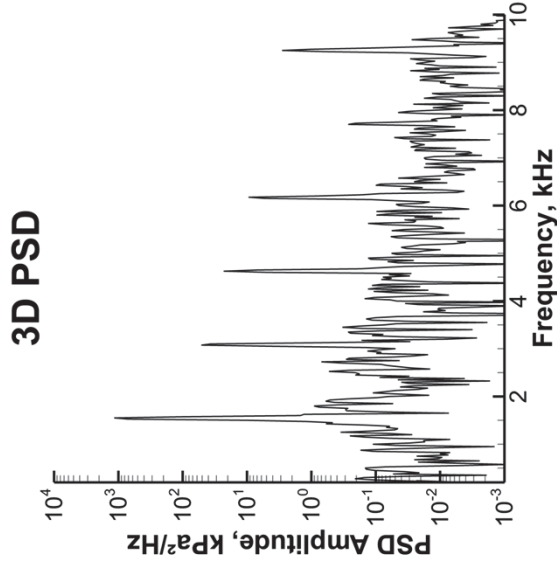


2D - Coarse Pressure Signal





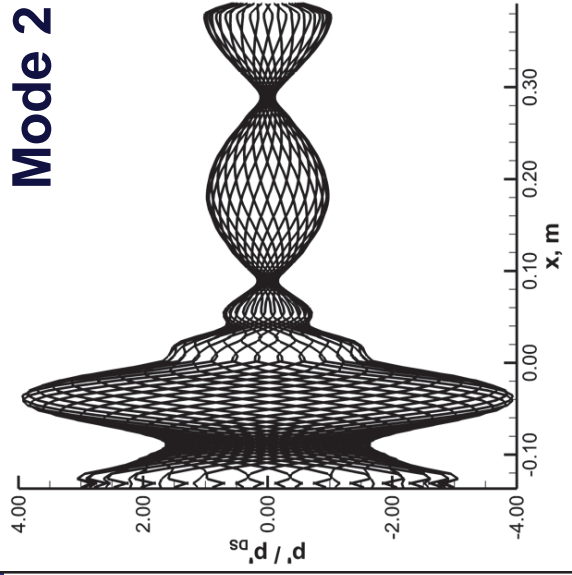
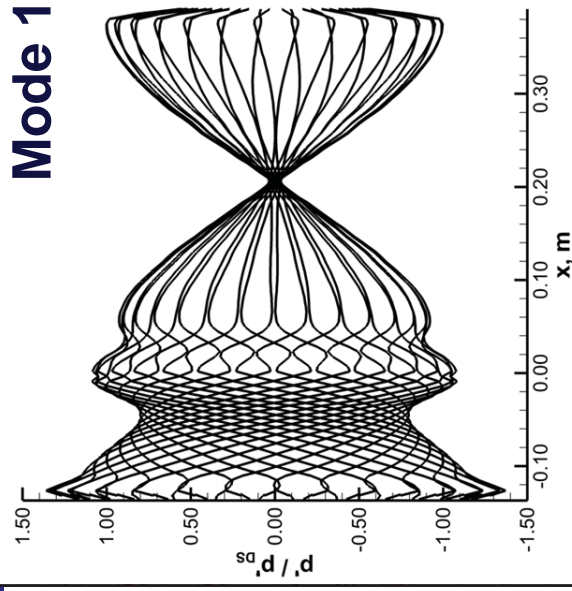
Power Spectra



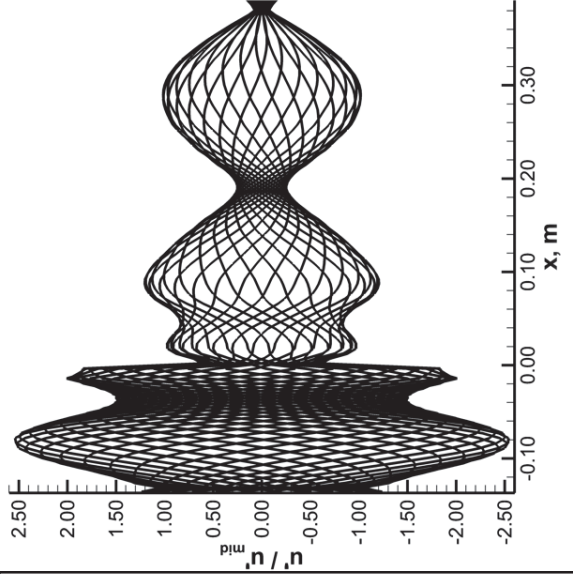
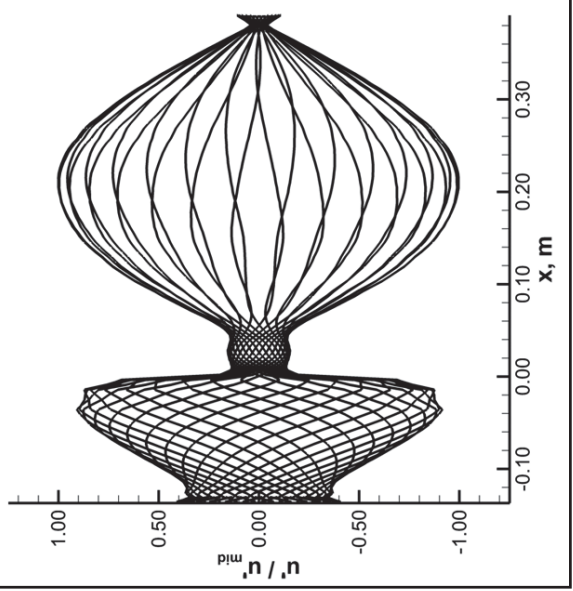


Mode Shapes

Pressure

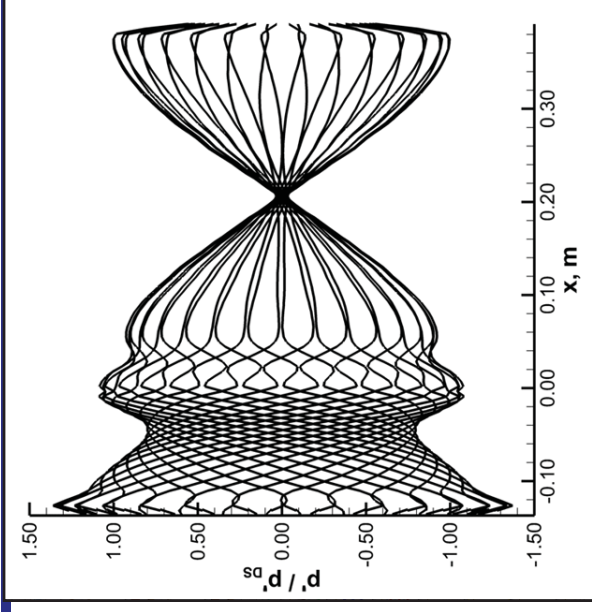


Velocity

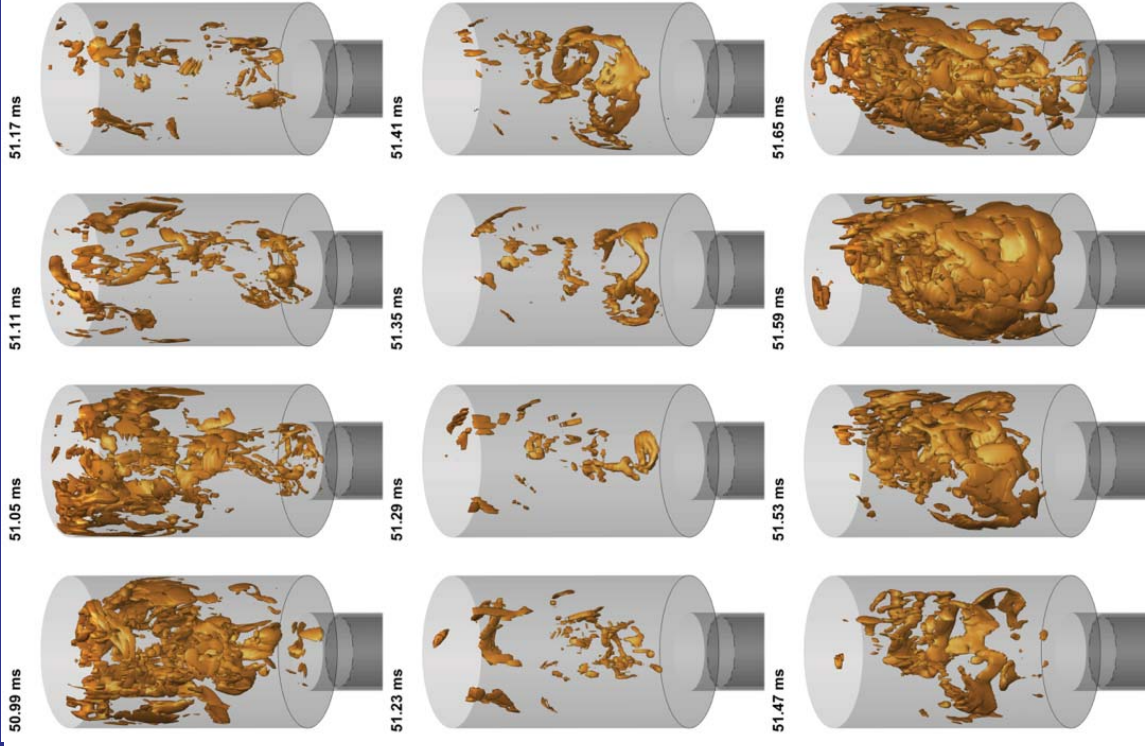




Instability Mechanism



- High pressure wave in oxidizer post returns half-way through the cycle
- Leads to pinching off of flame that serves as ignition when the high pressure wave returns in combustor

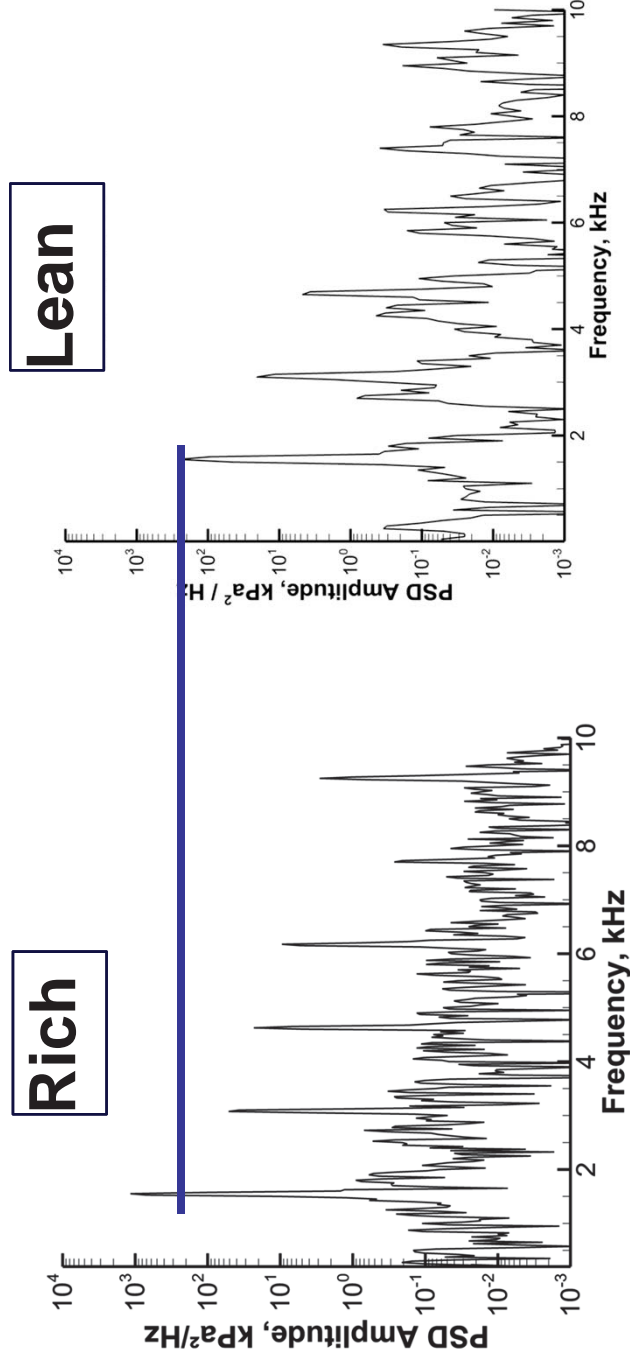




Rich vs. Lean

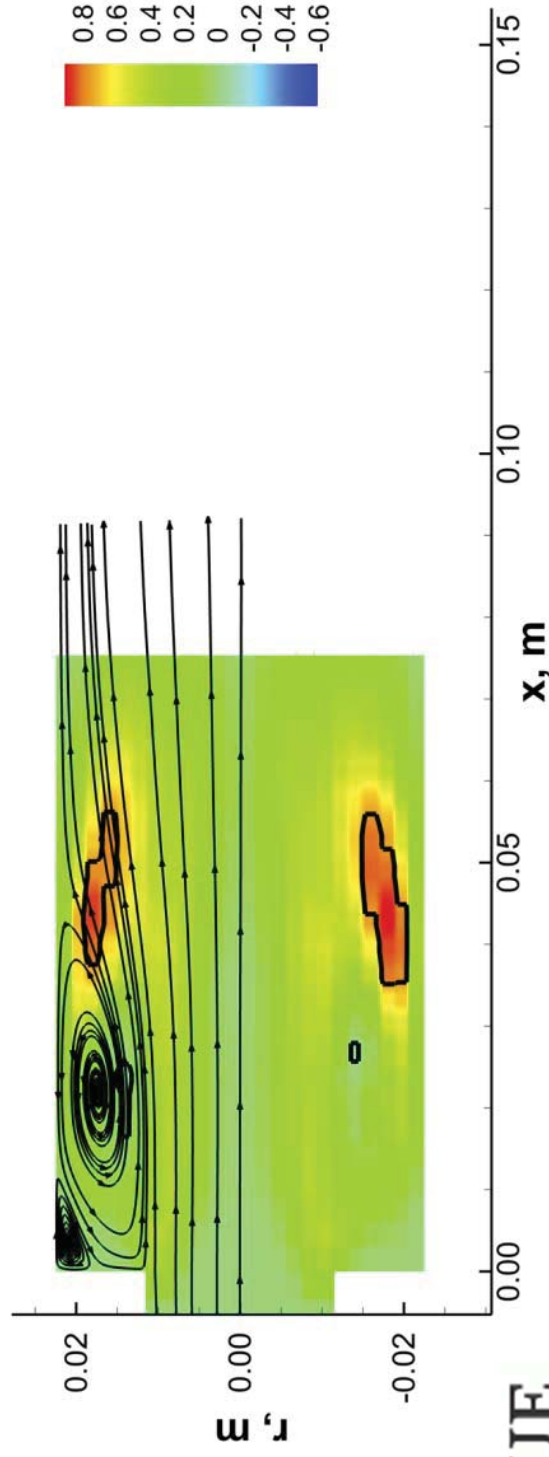
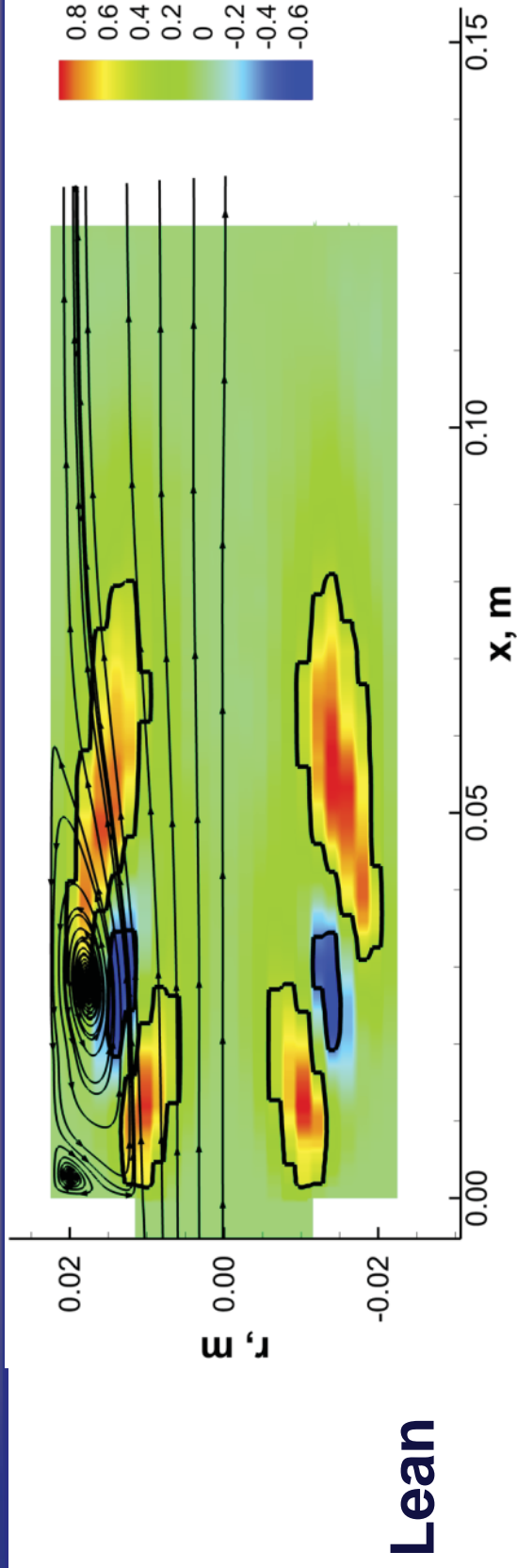


	Fuel Rich	Fuel Lean
Equivalence Ratio	1.4	0.8





Rayleigh Index



Rich

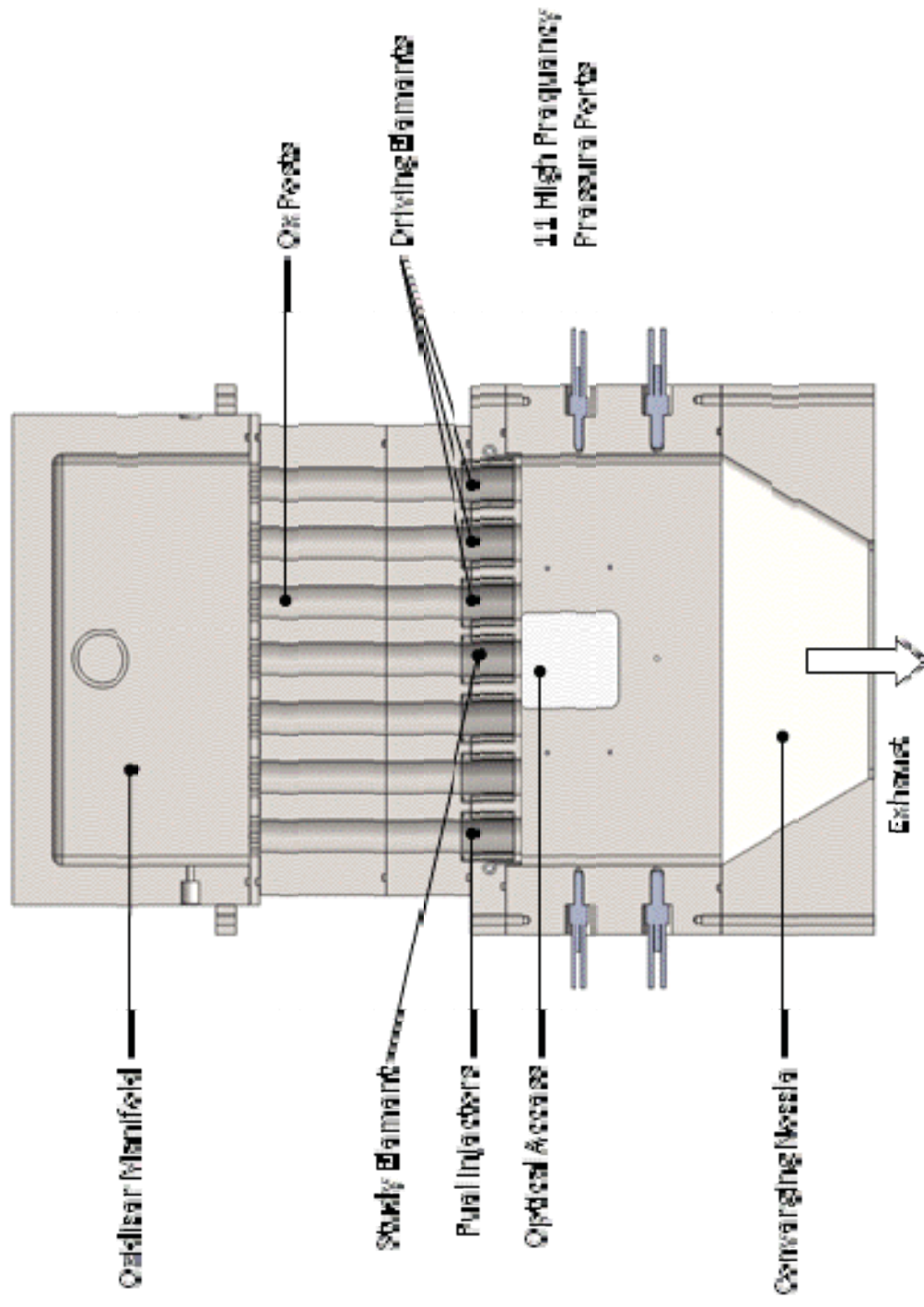
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Transverse Mode Chamber

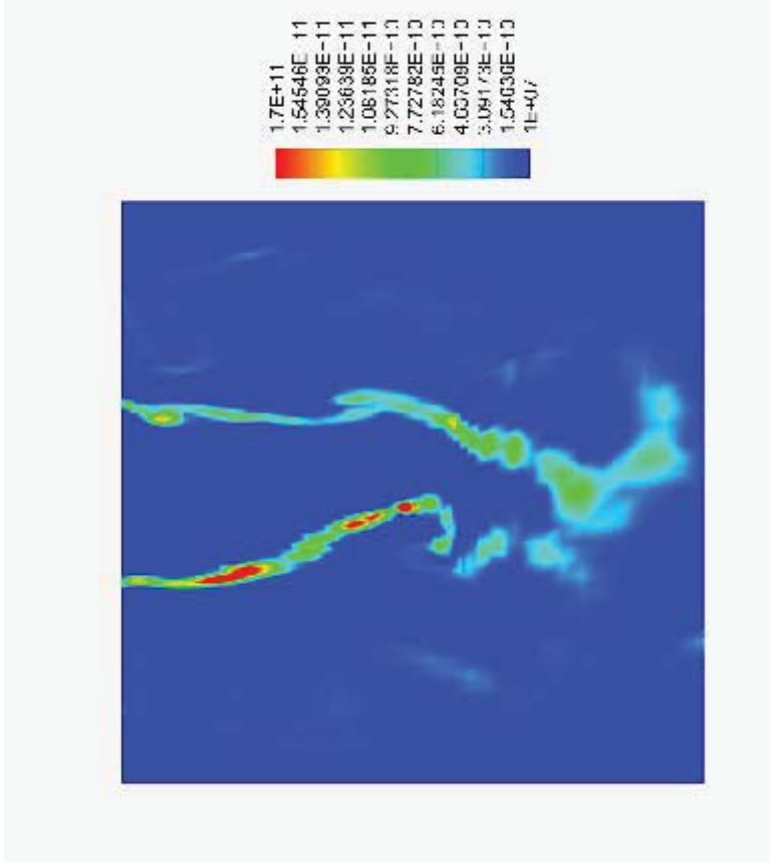




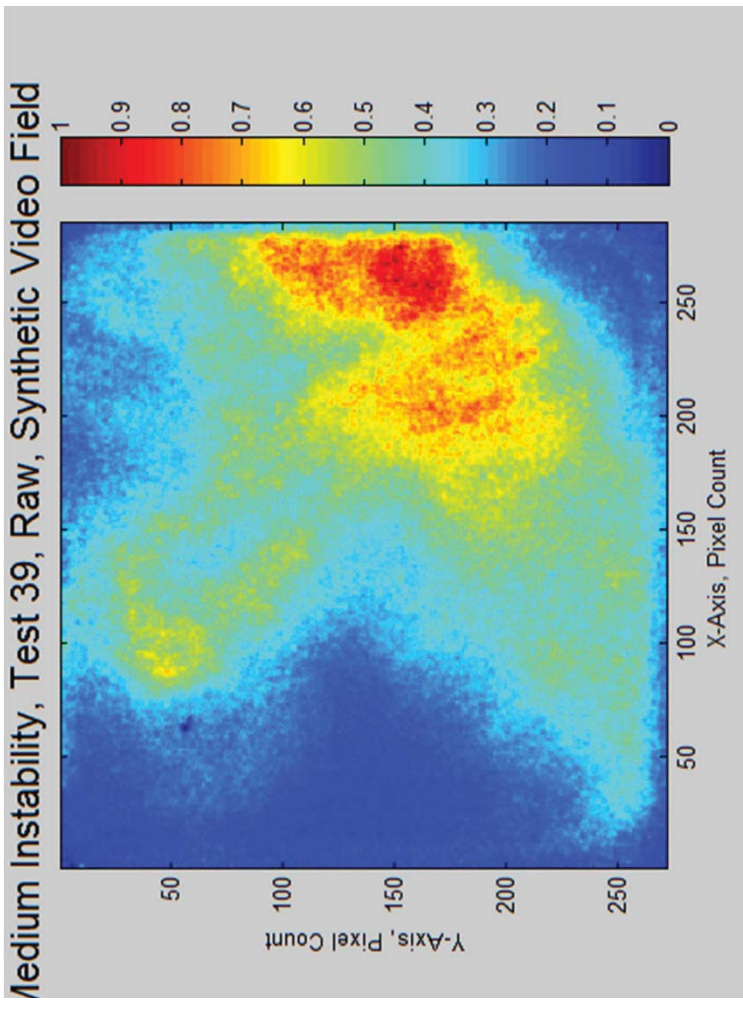
Heat Release



CFD Heat Rate (Watts)



Experiment Video - CH*





Future Directions

- **Turbulent Combustion**
 - Linear eddy models
 - Flamelets
 - FMDf models
- **Improved Accuracy**
 - High-order Cartesian
 - Adaptive mesh refinement
- **Improved Efficiency**
 - Algorithmic and Scalability Enhancements
- **Model Reduction**
 - Reduced-order models
 - Reduced-basis models





Acknowledgements



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